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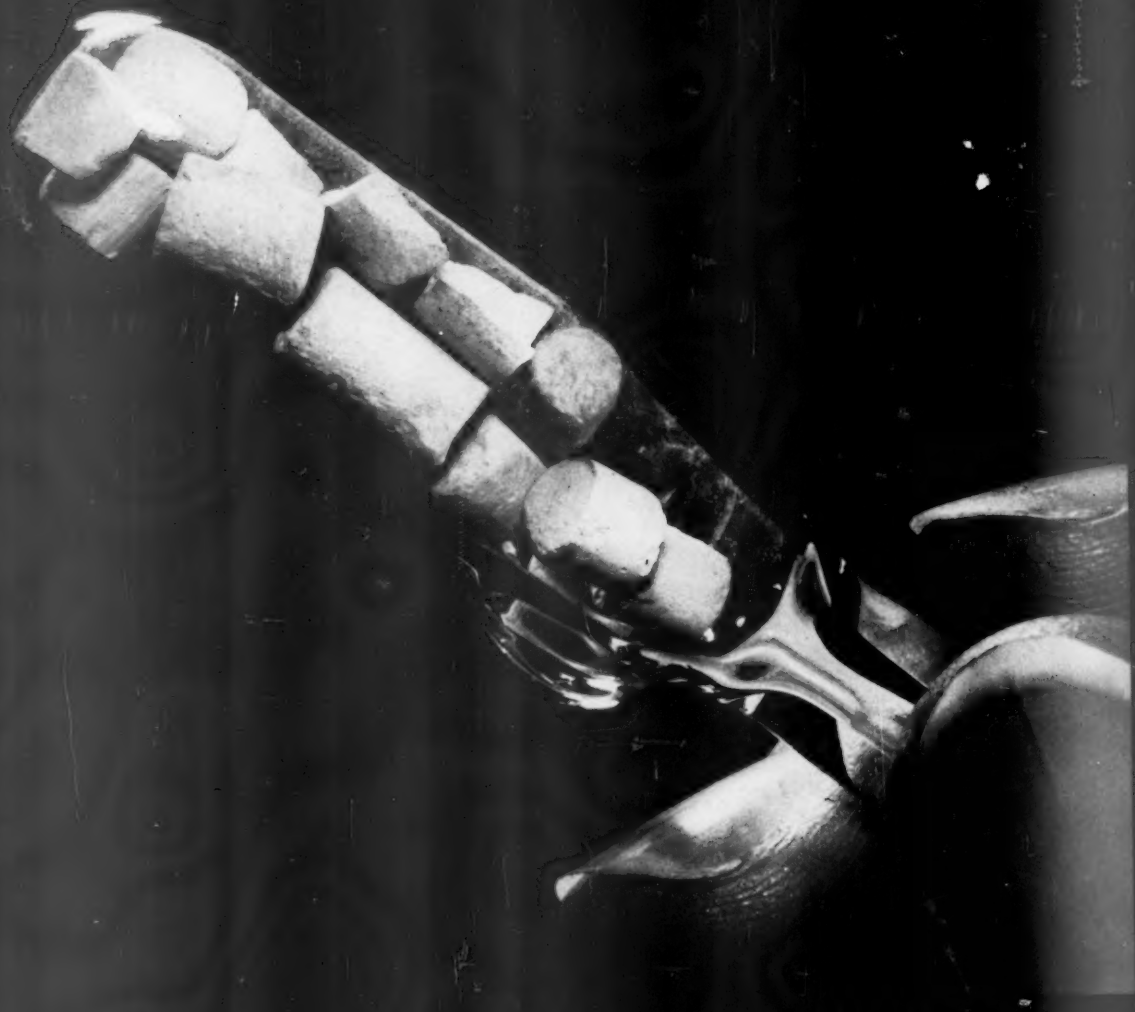

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On the Cover — Big as a barn is the true surface of the petroleum-cracking catalyst sample shown on the cover this month. The surface of the catalyst is 311 square meters, or about equal to the area of the four sides of a barn 50 ft long, 25 ft wide and 20 ft high. Development of information about adsorption phenomena is a contribution of the Battelle Memorial Institute about which an article appears on Page 11, Section 1.

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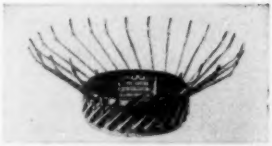

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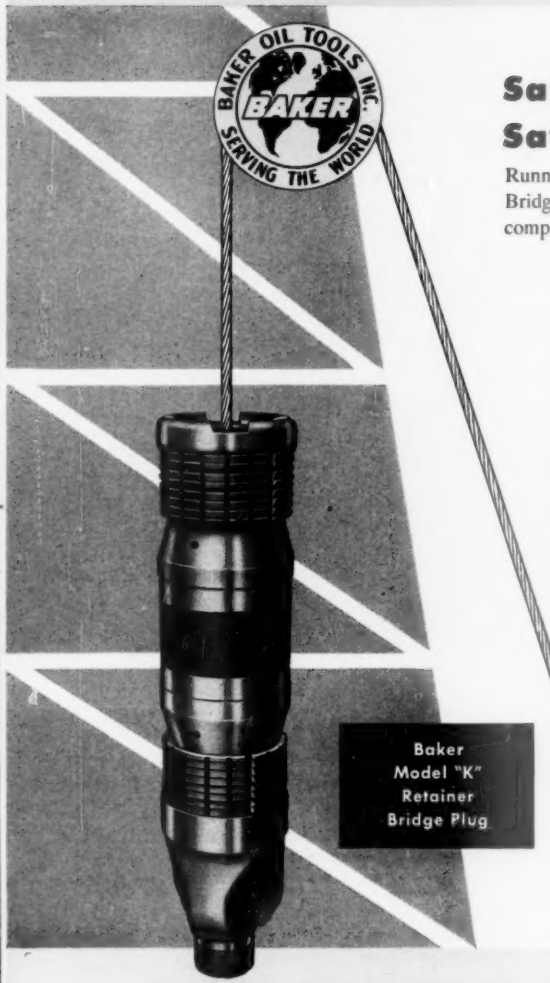

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Editorial Comment—

ON THE ESTIMATION OF UNDISCOVERED OIL RESERVES

By E. DeGolyer

DeGolyer and MacNaughton

SOME ten years ago L. G. Weeks and Eugene Stebinger, both of Jersey, made a worldwide study of sedimentary basins and a comparative analysis of oil finding experience. They "classified sedimentary areas still further as to their promise for oil, retaining for consideration only the more favorable areas where marine sediments occur in thick section." Wallace E. Pratt, then vice-president of Jersey, consulted these studies and apparently approved since he based upon them an estimate of ultimate discovery of 100 billion bbl of oil for the United States and 600 billion bbl for the rest of the earth. These estimates were presented in his notable *Oil in the Earth*, 1942.

The basic hypothesis upon which these and subsequent estimates were based, including Weeks' revision of 1948 to 110 billion bbl for the United States and 500 billion bbl for the rest of the earth, is now restated by Stebinger in the recently published *World Geography of Petroleum*. With oversimplification, perhaps, he recites, "assuming, as we have, uniform and continuous operation of the petroleum-forming processes through the ages, the result as applied to two given areas of great size and varied type should be proportional to the square miles of area involved."

I have always assumed that the relationship, if it exists, must be of volume of oil to volume of marine sediments and that area was used because it is an index to volume, though not too satisfactory. Weeks, in his *Concerning Potential Estimates of Oil Reserves* in the October, 1950, number of the *Bulletin* of the American Association of Petroleum Geologists, uses the volume to volume ratio.

It is difficult to consider critically the results of a technique of estimating for which one does not have the basic data. One may, however, examine the assumptions upon which the technique is based and the results secured through its application. The hypothesis, one must assume in fairness in spite of both Pratt's and Stebinger's comparisons of volume of oil to area of sediments, is that minable oil under current economic and producing methods exists in suitable sedimentary rocks throughout the earth in volume proportionate to the volume of such rocks.

THE first assumption of this hypothesis, stated and restated by its proponents, as Pratt clearly says, is that oil "is an inevitable result of fundamental earth processes; processes so typical that they have been repeated in each successive cycle of earth history" or, in summary, "that oil is a normal constituent of the marine sedimentary rocks all over the earth." Implicit in the hypothesis, if it be true, though not so clearly stated, is the assumption that oil once formed for large areas has been accumulated on averages everywhere equally into minable deposits.

I am not able to accept either of these assumptions.

The first is somewhat more palatable than the second. It seems entirely reasonable to me that the deposition of organic remains, if it is from such material that oil comes, is a normal sedimentary process but I wonder whether on averages it occurs at about the same rate throughout the world and throughout geologic time. Assuming, however, for the sake of argument that it does, I again doubt whether the little understood and complex processes necessary to convert it into oil are also effective on averages throughout world time and space. I note that Stebinger says, as to origin, "Nature is hiding an interesting natural phenomenon about as effectively as could be." More to my present point is Stebinger's "It is all too apparent that the oil forming process in its later stages, following the initial stage of the deposition of the sediments, is *highly selective*."

EVEN if all my doubts as to origin were resolved, however, I should be skeptical still as to the averaging out of the processes of accumulation; migration into suitable traps. Nor are my difficulties in this matter removed by Stebinger's "It appears, therefore, that great accumulations of oil and gas may be built up by short-range migration from compacting muds into adjacent sands very gradually and in minute quantities." This implies an inequality in deposition of source material which fits but illy with averages based on the original assumption of "uniform and continuous operation of the petroleum forming processes through the ages."

I have always considered that the great accumulations of hydrocarbons, such as East Texas with its five billion bbl or so of minable oil, Panhandle with its 38 trillion cu ft of producible gas and more than a billion barrels of oil, or the Burgan Field of Kuwait with its estimated 11 billion bbl of oil, are geological accidents. It seems to me that they are the result of extremely simple structure, extraordinarily large traps and migration up to long distances. A region such as the Appalachian, with a total productivity of not more than two billion bbl or so from hundreds of small pools, is the result of complex geologic conditions, both stratigraphically and structurally. The type of origin and short range migration suggested by Stebinger, whether they would be applied by him to the fields I have mentioned or to other fields, make any hypothesis of average occurrence difficult to accept.

THE supreme test of a hypothesis is that of the degree to which it is in accord with known facts. One may as well admit now that none of us will live to see exploratory drilling over the entire earth to the density postulated by Pratt. Basically the theory has seemed to me to be unsound since fundamentally it proposes an average distribution of the mineral hydrocarbons presently minable. The known minable mineral deposits of the earth are of notably unequal distribution. Even so simple a mineral as gypsum (also a normal sedimentary product) is distributed with great irregularity.

Elsewhere I have noted Pratt's citation that our country, with 11 per cent of the earth's total area of sedimentary rocks, has 45 per cent of the total estimated coal reserves. From this it may be derived that we have 4.09 per cent of the earth's coal per per centum of its area of sedimentary rocks while the rest of the world has only 0.616 per cent of coal per per centum of its area of sedimentary rocks. Thus the concentration of coal to area of sediments is more than six and one-half times as great for us as for the rest of the earth. If it be objected that coal, even though it also is of organic and sedimentary origin, is found under more highly specialized condition than oil, one may bear in mind Stebinger's view already quoted that the process of conversion of buried organic matter is also *highly selective*. Nor does coal have to undergo the further steps of migration and accumulation, also *highly selective*, to be minable.

A minable oil deposit is the result of a complex of events occurring over a long period of time. If we accept the theories currently orthodox it requires deposition of organic matter with the sediments, the preservation of such matter until conversion, its conversion into petroleum, the formation of traps suitable for accumulation and migration and accumulation into such traps. Any hypothesis of equal expectation of minable oil by volume or area of sediments over large areas presupposes that the effects of all these processes will average about the same or, in case of inequalities, that they will compensate.

In my opinion they are not likely to operate in any such fashion. One might with equal, apparent reasonableness note that sedimentation itself is a normal earth process and assume that its result, sedimentary rocks, is equally distributed on broad averages over the earth's crust. One might go into persuasive detail as to the processes of erosion, transport and deposition of sediments and so endow the assumption with an appearance of scientific probability. When we go to our maps to measure areas of sedimentary rocks, however, we find that our assumption is not valid. Less than 10 per cent of California consists of rocks in which we would not be surprised to find oil. Texas, on the other hand, consists of 90 per cent or more of such type of rocks.

WHAT of the known oil regions? They differ widely. As an index I note that a study made in PAW in 1942 showed that the average total production, past and future, for all producing oil wells which had been drilled in the United States was 61,000 bbl; east of the Mississippi, it was 11,000 bbl and west of the river, 114,000 bbl. Each of the last two estimates is an average over a very wide area, yet one is ten times as great as the other. The average production by states ranged from almost 7,000 bbl each for Pennsylvania and Ohio to almost 300,000 bbl for California. Interesting intermediate per well figures are 6,700 bbl for Indiana, 8,400 bbl for Kentucky, 34,500 bbl for Illinois, 45,000 bbl for Kansas and 169,000 bbl for Louisiana. By themselves these figures are suggestive rather than conclusive since they bear only on the richness of the actual oil deposits and not on the richness of the sediments as a whole.

Weeks notes, however, that there had been discovered in the United States up to January 1, 1950, nearly 64 billion bbl of oil or approximately 32,000 bbl of oil per cubic mile in the approximately two million cubic miles of basin sediments. He further notes that the various state or basin areas run from as little as 6,000 to 8,000 bbl for Kentucky and Indiana to as much as 200,000 bbl of oil per cubic mile for California. These estimates, in my opinion, give significance to the well figures.

Weeks' figures are as definite as can be at the present time. They are volume of oil to volume of sediments, which is precisely what we are talking about. If perchance there is some significance which has escaped me to Pratt's and Stebinger's use of ratio of oil to area of sediments, the well figures are acceptable at least as indices, yet for the Appalachian region compared to California, they vary as 1 to 33. If Weeks' volume figures are to guide us, they vary between Indiana, Kentucky and California as 1 to 25 or 33.

What, under these conditions and if this hypothesis is valid, do we use as a yardstick? Some 30 years ago I tried to make a reserve estimate for the entire earth by the area method, using North America as a yardstick. I used a continent to include a shield area, made an estimate for Canada, another for Mexico and Central America and used the United States Geological Survey estimate for the United States. The result of this arithmetical exercise was a figure absurdly low as events have proved. The late George Otis Smith, to whom I showed it, urged its publication for reason which he did not reveal. This reason, it transpired, was that David White's paper, *The Petroleum Resources of the World*, was then in press and Smith thought my estimate could be correlated with that of White. My figure was not published.

I CITE my experience merely to note that results depend upon the yardstick. Using the same method today, with Weeks' 1948 estimate for North America less 10 billion bbl assumed to represent continental shelves, one gets an estimate of 892 billion bbl which differs not too greatly (estimates being what they are) from Pratt's 700 billion bbl. I did not think my crude method was a sound one then nor do I think the more refined Pratt-Stebinger-Weeks method is a sound one now.

I have no particular quarrel barrel-wise with the estimates that have been made by use of the method under consideration. They may be too high. They may be too low. I do not know. I am inclined to think that Pratt's original estimate of 100 billion bbl for the United States may be too low even if we add 13 billion bbl for the continental shelves and that Weeks' recent estimate of 110 billion bbl, presumably including the continental shelves, is also too low. Leaving aside the apparently reasonable estimate of 10 to 13 billion bbl for the continental shelves, some two-thirds of the estimated 100 billion bbl for the land area will have been discovered by January 1, 1951. If we are prospecting for the last third of our total oil resources and only 33 to 35 billion bbl remain to be discovered, there is nothing in our present very satisfactory discovery rate to indicate that we are approaching the bottom of the barrel. There should be if this is true. ★ ★ ★

Battelle Memorial Institute and The Petroleum Industry

By Frank C. Croxton

Assistant Director, Battelle Memorial Institute

An Independent Researchist Comes to Advance the Cause of Independent, Nonprofit Research Organizations and Describes Some of the Projects Carried Out to Advance the Technology of the Petroleum Industry.

BATTELLE Memorial Institute is one of the group of independent, nonprofit research laboratories which have, in a relatively few years, assumed an important place in American technology through their services to industry. A substantial portion of the activities of these institutes deals with the petroleum industry, its problems, and its products.

It is the intention to describe here some of the petroleum projects which have been handled by Battelle. Thus, it may be seen how the independent laboratories can supplement the research departments of the larger companies or act as the sole research facilities of smaller firms having none of their own.

One of the Institute's first petroleum problems was fundamental in character. Sponsored jointly by the Atlantic Refining Co. and Battelle Institute itself, it was a study of the mode of action of lead naphthenate-free sulfur, extreme-pressure lubricant additives, using electron-diffraction apparatus as a tool. Friction treatments were carried out on steel surfaces in a simple laboratory apparatus for light loads, and in an S.A.E. machine for heavier loads. Gears from two hypoid units which had been run exclusively with lead naphthenate-free-sulfur lubricant for 20,000 miles were also investigated. It should be kept in mind that an electron beam of this sort penetrates only a few molecular layers and so provides data on the structure of the surface or of a surface film, if there is one. On the basis of the results from this study, it was concluded that lead naphthenate plus free sulfur has a greater film-forming tendency in unrefined oils than in those which are highly refined. At 150°C, an initial layer of lead sulfate is formed with a superimposed film of lead sulfide. At 300°C, however, the lead sulfate becomes only a trace, while the lead sulfide predominates. Examination of the hypoid gears which had been run 20,000 miles in lead naphthenate-sulfur-type lubricant exclusively showed iron oxide and a new phase which proved to be very probably lead sulfide rich in lead. Two points should be noted. First, the iron oxide on the gear teeth could be produced in the laboratory by use of sulfur, alone, as additive. Second, the availability of oxygen is essential in considering the chemistry of this type of extreme-pressure additive.

At about the same time, Battelle was asked by the major producers of selenium in the United States and Canada to study the technical factors involved in expanding the markets for selenium and tellurium. Significant contributions were made in the fields of selenium rectifiers and selenium ruby glass, but it is the organic chemical research that should be emphasized here. It is well known that selenium dioxide, one of the commercially available forms of the element, is an effective oxidizing agent. It was not unreasonable to believe, then, that the addition of small quantities of selenium dioxide to drying oils such as linseed, might hasten drying through more rapid oxidation. A small-scale trial of the idea was in order, but it was observed that the oil failed to dry at all. Apparently the selenium compound was acting as an antioxidant. Thus began what has now developed into a sizeable study of selenium in lubricants, including its action as antioxidant, detergent, and extreme-pressure agent.

Selenium dioxide is not appreciably soluble in petroleum products, but the addition of a little alcohol, such as 2-ethylhexyl, gives adequate solubility for antioxidant action. Studies with the Indiana and underwood oxidation testers, Lauson, Chevrolet, and Ford engines, and road tests have given abun-

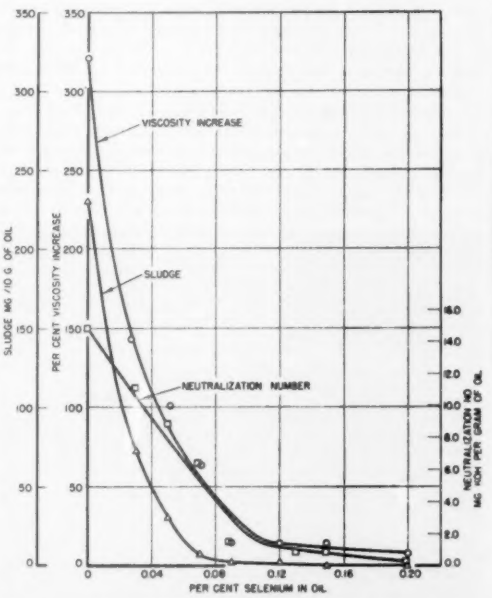


FIG. 1 — TEN-HOUR UNDERWOOD OXIDATION TESTS WITH SELENIUM DIOXIDE-2-ETHYL HEXYL ALCOHOL IN PENNSYLVANIA 10W BASE OIL.

dant evidence of the antioxidant and detergent actions of selenium in the form of several of its compounds. An attractive feature is the comparatively small amount of additive required, thus allowing the refiner to sell more oil and less chemicals. Laboratory test data show an apparently safe figure of 0.15 per cent selenium which corresponds to but 0.21 per cent selenium dioxide or 0.63 per cent oxide plus alcohol. Selenites, selenonophosphates, and diselenides have also been found to be effective. Fig. 1 shows the effect of selenium concentration on several properties of a 10W oil in the Underwood Oxidation Test.

AS A chemical relative of sulfur, it might be supposed that selenium, in the form of appropriate compounds, would be an effective extreme-pressure agent. Evaluation work at Battelle has shown that supposition to be valid. Selenites, selenonophosphates, and diselenides are of interest here, too. Fig. 2 gives a comparison of base oil alone and the same base oil with (a) 6.5 per cent commercial e.p. additive, and (b) 4.5 per cent tributylselenonophosphate, using the Shell Four-Ball Extreme Pressure Lubricant Tester, which shows the oils containing additives to have similar seizure and weld loads which are far above those of the base oil. It is to be emphasized that these are screening tests to select the most promising additives for the comparatively expensive full-scale axle tests which are in progress at the present time.

The broad scope of Battelle Institute's research has attracted a number of projects designed to discover new uses for known products. Such uses, and ultimately markets, can be sought in the fields of welding, graphic arts, combustion, ceramics, metallurgy, chemistry, agriculture, and numerous others. It is logical, therefore, for Battelle to screen such products as selenium, copper, vegetable-oil phosphatides, and specialty organic chemicals, as lubricant additives in the course of searches for new uses for them which are currently in progress. It is surprising to find that certain oil-soluble copper compounds act as antioxidants in lubricating oils, in view of copper's well-known reputation as an oxidation catalyst.

Reference has been made to the oxidizing action of selenium dioxide, an effect produced by actually depriving that compound of its oxygen. A program of fundamental research at Battelle, several years ago, discovered some very unusual behavior by certain metal selenities when used as oxidation catalysts. Typical of this are the following reactions which outline the conversion of cheap olefin hydrocarbons to the corresponding unsaturated aldehydes and acids.

$$CH_2=CH-CH_3 + O_2 \xrightarrow{Ag_2SeO_3} CH_2=CH-CHO + H_2O$$

Propylene — Acrolein

$$CH_2=C(CH_3)(CH_3) + O_2 \xrightarrow{Ag_2SeO_3} CH_2=C(CH_3)(CH_3) \quad H_2O$$

Isobutylene — Methacrolein

$$CH_2=CH-CHO + \tfrac{1}{2}\,O_2 \xrightarrow{Ag_2O} CH_2=CHCOOH$$

Acrylic Acid

$$CH_2=C(CH_3)-CHO + \tfrac{1}{2}\,O_2 \xrightarrow{Ag_2O} CH_2=C(CH_3)-COOH$$

Methacrylic Acid

The most obviously useful are acrylic and methacrylic acids, whose polymerized esters are well known as clear, rigid plastic sheets and as adhesives. This offers a method for making a widely used type of resin by direct oxidation of inexpensive raw materials derived from petroleum.

Battelle has, for some years, been active in the development of corrosion-resistant materials and methods for the correction of corrosion in service. The result of a corrosive condition in a refinery absorption tower was brought to the Institute's attention. This constituted a portion of a corrosion study made recently by Battelle. Since the wall of the tower was comparatively thin, it had been concluded by the fabricator that it would be unnecessary to take steps to relieve the stresses remaining after welding on a bracket. The resulting stress corrosion was destructive and expensive, as may be seen in Fig. 3. Battelle's recommendations should enable the sponsor to avoid difficulties of this sort in the future.

MANY trade associations and other groups with similar interests look to the independent, nonprofit research institutes for help in the solution of their technical problems. For two years Battelle, under sponsorship of the American Association of Oilwell Drilling Contractors, investigated the short service life of numerous drill strings in the Permian Basin. As just one phase of the problem, a comprehensive survey of the technical and patent literature dealing with nondestructive testing methods was made and published. Field and laboratory work have shown that some joints failing in service should have been rejected in the mill. Used pipe, too, may contain defects which, if undetected, will lead sooner or later to washouts and twistoffs plus the expense of fishing and replacing. Battelle has made a number of recommendations for inspection of pipe at the mill, routine inspection of used joints each time the string makes a trip out of the hole, and even for improved drilling practices to reduce string failures. A laboratory apparatus for accelerated corrosion-fatigue testing essentials in the development of improved materials for drilling service was designed and constructed. It has been very helpful in studying inhibitors, such as sodium chromate, and the effects and limitations of organic coatings.

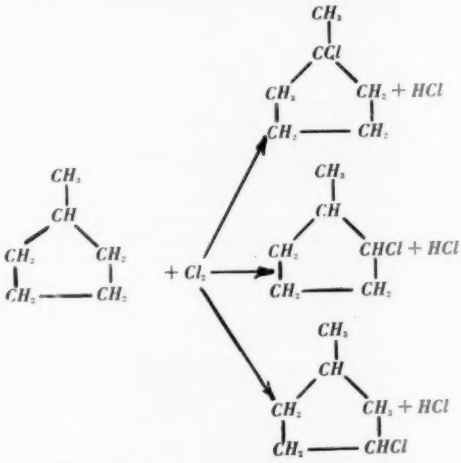
Further, with reference to corrosion and its prevention, the Pennsylvania Grade Crude Oil Association has sponsored research at Battelle on such problems encountered by air-gas-drive secondary recorvery operators. From this work have come several promising inhibitors, including sodium chromate and Calgon, and evidence, as shown in Fig. 4, that much can be realized from the use of galvanized tubing and rods, especially at the most corrosive levels.

In 1943, palm oil was available only in very small quantities and its future was quite uncertain. Under the sponsorship of Shell Oil Co., Battelle began work on a project to develop a mineral-base rolling lubricant for the cold reduction of steel to tin-plate gages. A satisfactory substitute for palm oil was the immediate goal. A fundamental approach was used and a laboratory rolling mill was set up to simulate plant practice and to measure friction coefficient particularly. Several materials were found which reduced friction more than palm oil did, but to avoid roll slippage, a lubricant was compounded which behaved exactly like palm oil in that respect and met other requirements satisfactorily. Photomicrographs showed poor luster to result from tearing of the surface, a rather graphic manifestation of the stick-slip phenomenon described by Bowden and others in their work on lubrication theory.

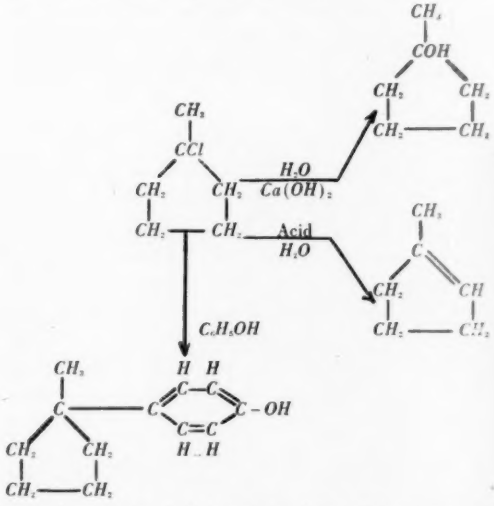
Chemical products have had much attention from petroleum refiners during recent years. The steady, day-to-day avail-

ability of raw materials, many of which can ve valued at only fuel equivalent, and the trend toward more "chemicals" as additives in both lubricating oils and fuels have directed the thinking of many refiners toward the chemical-product field. Butadiene and toluene during the war had much to do with this.

WITH Standard Oil Co. (Indiana) as sponsors, Battelle Institute studied some of the chemistry of methylcyclopentane, a hydrocarbon which can be separated fairly readily from certain naphthas, by distillation. Some of the more obvious reactions were tried, as follows:



Considerable new information on properties and structures was uncovered. In turn, the reactions of the monochlorides were investigated, as typified by the following:



The chlorides, the alcohols and the olefins all have potential uses as solvents and as precursors of other compounds, such as esters. Furthermore, the general principles demonstrated by methylcyclopentane may be applied to methylcyclohexane and related hydrocarbons available in quantity from petroleum.

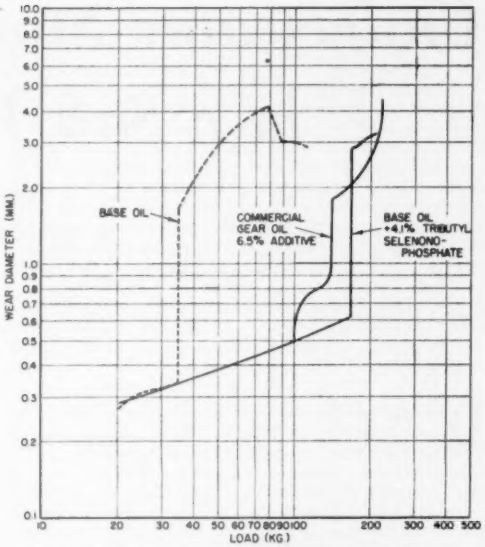
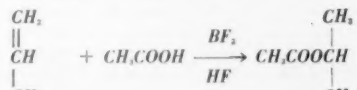


FIG. 2 — SHELL FOUR-BALL EXTREME-PRESSURE LUBRICANT TESTS.

At the same time, and for the same sponsor, research on certain aspects of olefin chemistry was in progress. An interesting development was that dealing with the production of esters from organic acids and, not alcohols, as is usual, but olefins. An example is the following:



Propylene — Isopropyl Acetate

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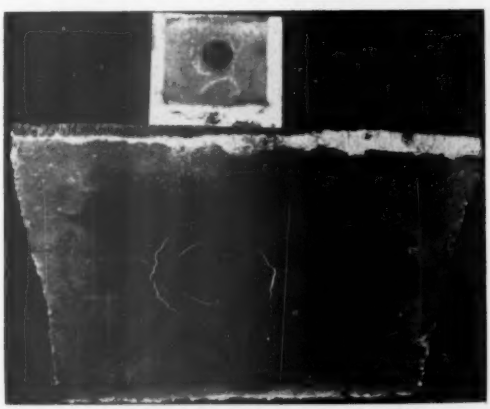


FIG. 3 — STRESS CORROSION IN AN ABSORPTION TOWER.

Underwater Storage of Propane in a Salt Water Sand

By Charles B. Johnson, Jr.

Chief Engineer, The Chicago Corp.

DETAILS of the first cycle of operation of the Underground Storage of Propane Project in the Carthage Field were given in a previous discussion.* Therefore, the following data are a partial review and a summary of economic factors favoring this method of storage. These factors include the wide market fluctuations due to seasonal demand, the high cost of surface storage and, since 1948, an oversupply due to new plant construction, expansion of existing plants and increased extraction efficiencies.

The factors are interlocking since they are all pertinent to the ultimate goal which is the maximum return per unit of money invested. Fig. 1 is a history of prices received per barrel of propane at Carthage and the volume of propane manufactured in the United States. The seasonal highs are outstanding and the downward trend in prices correlates closely with the increasing volume. As a matter of interest, it is noted that the price was abnormally depressed during the winter of 1949 and 1950 due to unusually warm weather that minimized the use as a heating fuel, which constitutes one of the larger markets for propane. Taking the month of January as the peak market period, the effect of additional output is best illustrated by comparing the actual production for the three years. There was an increase of 380,000 bbl per month from 1948 to 1949, and 670,000 bbl per month from 1949 to 1950 for an overall increase of 1,050,000 bbl which is some 66 per cent in the two-year period.

The growth of the propane market is shown by the higher level of the "lows" which have occurred in June of each year, but the relatively more rapid increase in supply is outstanding in that where the high-low differential in 1948 was 440,000 bbl, that in 1950 has been 750,000 bbl.

Without a market and without storage, the propane can be disposed of only as a vapor which at standard conditions is 1,531 cu ft per barrel and at current gas pipeline prices brings 8 cents per barrel. Comparing this figure with an assumed spot market low of as little as 1 cent per gallon, the absolute minimum ratio of expected return for sale as a liquid is just over 5:1 which leaves ample latitude for installation of storage facilities. However, the pressure rating required for propane tanks plus the dimensional restrictions call for a sizable expenditure and consequent long, high rate of amortization of investment. By way of illustration, 1,000 bbl capacity propane tanks have cost $16.50 per bbl installed.

Considering the project at Carthage, it was estimated that the off-season storage would approximate 150,000 bbl which, for tanks alone, would cost some $2,500,000. This obviously provided incentive to attempt use of subsurface storage.

ASSUMING that the initial stored volume would be 100,000 bbl and that any losses would be at the rate of 8 cents per barrel, Fig. 2 was constructed to illustrate the rate of payout for an investment of $250,000 at various prices and three net recovery efficiencies. It was assumed that a portion of the originally injected propane would not be recovered due to unavoidable underground loss or impracticability of recovery and that the take from storage per season might not include the fully recoverable volume.

With the minimum price at 1 cent per gallon, it is seen that 25 per cent recovery would require 24 years to pay out and was therefore unsound but at 50 per cent the payout time is reduced approximately one-half, while at 75 per cent it is just

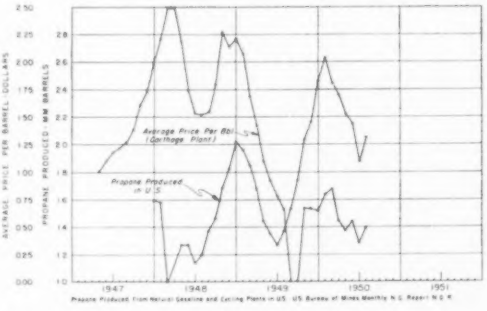


FIG. 1 — PRICE RECEIVED PER BARREL OF PROPANE AND VOLUME OF PROPANE PRODUCED IN THE UNITED STATES.

*Proceedings, N.G.A.A. Twenty-ninth Annual Convention, Fort Worth, Tex., April, 1950.

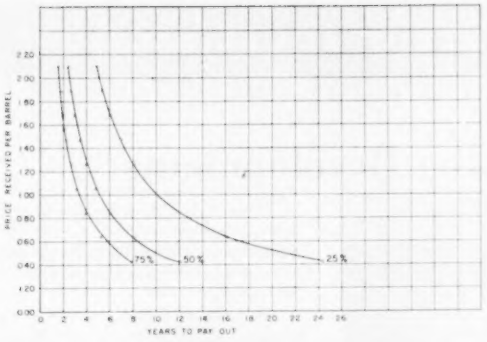


FIG. 2 — SUBSURFACE PROPANE STORAGE, RATE OF PAYOUT OF VARIOUS MARKET PRICES FOR RECOVERY EFFICIENCIES OF (1) 25 PER CENT PRODUCED IN 120 DAYS AT 208 B/D; (2) 50 PER CENT PRODUCED IN 120 DAYS AT 416 B/D; (3) 75 PER CENT PRODUCED IN 120 DAYS AT 625 B/D.

under eight years. These values are ultra-conservative with respect to the price received and for the two lower recovery efficiencies are definitely on the non-optimistic side with regard to expected recovery. A more realistic but still conservative price should be 3½ cents per gallon ($1.47 per bbl) which increases the payout rate to seven years, three and one-half years, and two years, respectively.

The Propane Subsurface Storage Project at The Chicago Corp.'s Carthage Plant was originally planned for a total volume of 150,000 bbl, but from inception to first withdrawal for market, only about one-third this capacity was utilized. Excluding the quantity withdrawn on intial tests, a net of 26.8 per cent of the stored propane was marketed during the first year of operation.

BY way of review, the original plan called for a four-spot water flood type well pattern with the injection well at the center. The first "relief-flood" well had poor permeability and is therefore only partially effective. The second "relief-flood" well had excellent permeability and a thicker section than the injection well but the propane-water interface reached this well when 70,000 bbl had been injected. Two additional wells lacked an effective sand section. The map, Fig. 4, is an isopachous map of the storage reservoir superimposed on a structure map of the Paluxy sand. It appears from the control provided by the wells drilled to date that there is sufficient volume for more than 1,000,000 bbl in this reservoir.

All withdrawals so far have been without benefit of mechanical or artificial means to cause flow of propane to the surface. It is apparent that the driving force has been provided by the compressibility of gas dissolved in the salt-water since at the prevailing pressures and temperatures the compressibility of the liquid propane is practically nil. It is also apparent that the reservoir is in communication with the main Paluxy sand through a permeability barrier since the maximum pressures reached continue to decline for a considerable period of time after injection has been stopped.

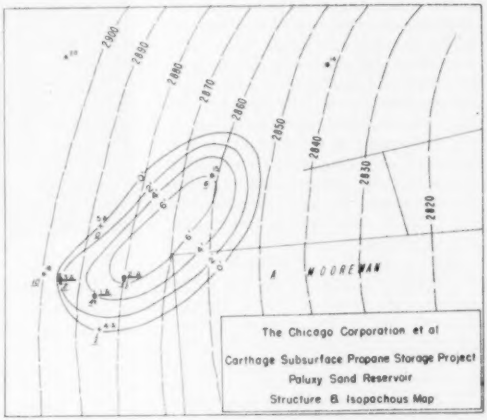


FIG. 4 — THE CHICAGO CORP., ET AL., CARTHAGE SUBSURFACE PROPANE STORAGE PROJECT PALUXY SAND RESERVOIR STRUCTURE AND ISOPACHOUS MAP.

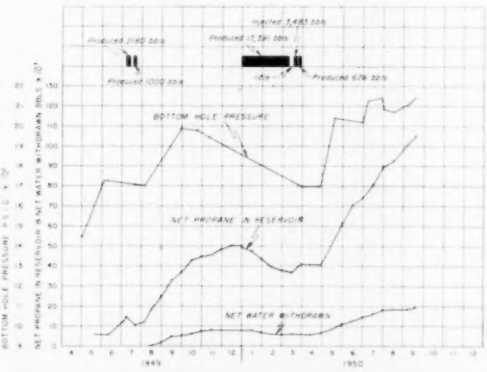


FIG. 3 — THE CHICAGO CORP., ET AL., CARTHAGE SUBSURFACE PROPANE STORAGE PROJECT OPERATIONAL DATA.

The overall performance to date is illustrated in Fig. 3. The first test, during July, 1949, produced 3,180 bbl of a total injected quantity of 14,087 bbl or 22.6 per cent. Withdrawal for market commenced January 1, 1950, at which time a net of 50,038 bbl of propane was in storage, and 13,391 bbl or 26.8 per cent was withdrawn to the first part of March. The bottom hole pressure behavior followed the trend of a constant volume type reservoir and the previously noted tendency of pressure stabilization due to communication with the main sand body is shown by the variations in the curve.

At the present, 105,000 bbl of propane are in the reservoir and it is probable that withdrawals will begin shortly. The planned procedure involves backflowing at a rate of 500 bbl or more per day which can probably be sustained by conversion of the present propane injection well to water injection and, if necessary, the use of mechanical pumping equipment.

Although this project is still experimental, tests to date have proved the feasibility of this method of storage. Definite conclusions regarding the economics may be drawn at the end of the forthcoming market period. ★ ★ ★

PACIFIC JUNIOR GROUP

Directional Surveying Developments

By Wm. G. Paul, Jr.

Ray Mahan, a chemical engineer and general manager of the Servco Corp., an organization engaged in providing non-magnetic drill collar service for directional surveys, spoke Dec. 14 to members of the Pacific Junior Group in Downey, Calif.

Development of the K-Monel drill collar began around 1940 to meet the need for a simpler, more reliable method for directional surveying of the drilling well course. At that time there were two methods commonly employed for running the survey tool. The first, or open hole method, required removal of the drill string from the hole, subsequent to which the survey instrument would be lowered by wire line and the picture taken. The major problem with this method was, of course, the time lost in pulling and re-running the drill string. A secondary problem was that of aligning the survey instrument in the open hole to insure accuracy of measurement. The second method involved the use of a center bit or trigger bit. With this type bit in use, the survey instrument could be lowered through the drill string and bit into the open hole for the shot. While this method did not require drill string removal, there was still the alignment problem and additional problems caused by the danger of hanging up while pulling the instrument back through the bit, and the drilling limitations of the bit itself.

Early testing included three alloys: K-Monel, beryllium copper, and two types of stainless steel. Their properties compare with AISI 4140 steel, a common drill collar material, as shown in Table I.

While beryllium copper showed several good qualities, its use was abandoned due to prohibitive cost. Stainless steel was found to work harden and become magnetic in use. From Table I, the similarity in physical properties of Servco K-Monel and AISI 4140 is apparent, and testing proved it to be a logical choice for this service.

Mahan emphasized that experience has proven the necessity for providing the K-Monel collar as an engineered service. Some of their early problems

RAY MAHAN

verify this belief. At first, two lengths of drill collar, 14 ft and 23 ft, were utilized. These were placed in the drill string just above the bit, and when a survey shot was desired the instrument could be lowered into the collar and the picture taken. In many cases, the pictures taken in this fashion were checked with open hole and multiple shots. This comparison brought out the importance of well bore angle and direction on the length of collar necessary to avoid magnetic attraction of the compass needle by the steel drill collars and bits. It was found that magnetic influence of steel drill collars above the K-Monel would affect the compass at points where the well course changed direction. As the hole angle increased this influence was likewise found to increase. Also, it was later discovered that magnetic attraction would vary considerably between drill tools of the same material in different operations.

This experience tended to dictate the length of collar necessary for different operations to avoid having an erroneous reading due to attraction from steel in the drill string. The application was complicated, however, by the higher angles of drilling experienced in later years. The collar to be most desirable from a magnetic immunization standpoint might be too long to permit high rates of change in the well course. Mahan again used this factor to bring out the necessity for an engineered application. Today there are available 32 different types, lengths, and sizes of K-Monel collars to meet the requirements of modern drilling. With proper application they have successfully operated in controlling both straight and high angle holes. Angles up to 80 per cent have been successfully experienced.

Mahan concluded by stating that at the current stage of development, the single shot in K-Monel is often the only one taken, and is considered by many operators to be the standard with which other shots are compared. He listed the four major advantages of K-Monel as: (1) Highest accuracy due to alignment of instrument with bore hole in collar and alignment of collar with the hole itself. (2) Greatest safety in use of wire line tools, and through the new "drop type method" of surveying, elimination of all wire line operation. (3) Faster hole due to minimum down time in the survey operation and since the most appropriate bit can be utilized. (4) Smoother, straighter hole permitted by frequent checks of direction and on the spot correction. ★ ★ ★

Table I

	Stainless Steel AISI 303	Stainless Steel AISI 347	Beryllium Copper	Servco K-Monel	AISI 4140
Yield Strength, psi	35000	40000	171000	121000	116000
Tensile Strength, psi	87000	95000	200000	155000	142000
Elongation in 2", %	60	60	2.8	23	22
Reduction of Area, %	55	65	—	54	62
Hardness, Brinell	160	145	400	278	293
Magnetic Permeability	1.003	1.001	1.000	1.000	Magnetic

NORTH TEXAS SECTION

The Petroleum Industry and Wartime Conditions

By John Jacobs

Charles J. Deegan, of the firm Cummins and Brinkerhoff, Fort Worth, Tex., told members of the North Texas Section at their mid-December meeting that the time has come again for the petroleum industry to take stock of itself to determine if it is ready for wartime conditions. A condensation of Deegan's talk follows.

You are engineers in an industry that is important to our country's welfare in peace — and a vital necessity in time of war. Over the coming months — and years — you are going to have to shoulder some heavy responsibilities. Because of a portion of my past experience, it is my unpleasant task to try to prepare you for what lies ahead.

You know that the first step in any engineering problem is to determine the scope of the problem and the basic factors involved. The basic factors in your future personal problems will be parts of world-wide basic factors. Your personal problems will be of very great magnitude, because oil is of worldwide vital importance.

Until you appreciate the full scope of the overall problem, you will be continually coming up with plans that are tragically "too little - too late" as far as your individual problems are concerned. This will be true, because unless you appreciate the full scope of the overall problem, you will be constantly underestimating the magnitude of the basic factors involved in your individual situations.

Under present conditions it is foolish to compare our oil and steel production to that of the Communists. Nearly all of their steel and oil goes directly into things to fight with. Nearly all of ours goes directly into things to make life more pleasant for our people. In actual barrels of oil and tons of steel, they have been putting far more into things to fight with than we have. They have millions of trained men uder arms. By comparison, we have only a handful.

That condition must change and it will change quickly. As it changes, you as petroleum engineers are going to have very serious problems.

You are already facing at least minor annoyances in material shortages; and I'm not talking about just tubular goods. These material shortages are going to get a lot worse as time goes on. People who should know how things look from Washington will tell you that conditions in the last war will look like a Sunday School picnic by comparison with what lies ahead. Personally I think that's a sound prediction.

CHARLES J. DEEGAN

What can you do about materials? Well, a first sensible step is to get the facts. Take an inventory of what you have on hand in two categories: (a) equipment in use; and (b) stock of replacement and repair parts.

The bulk of your inventory will be equipment already in use. It will probably have to last you a long time. Wouldn't it be a smart idea to check up on your general maintenance program?

The first step in improvement of any maintenance program is better housekeeping. A neat, clean operation pays profits in many ways. Over any five-year peacetime period it saves substantial amounts of money in maintenance and replacement costs. What will it save when replacement parts can't even be bought for any amount of money?

When your lease is kept clean, equipment and buildings neatly painted, with weeds and grass kept cut down, then the effects of wear and tear in small items show up quickly. Around a clean, brightly painted lease battery, small leaks, or slightly worn valves and fittings show up quickly and are repaired while they are small items. If the area around a pumping well is scraped and kept clear of punk, high grass and weeds, your pumpers will see many a loose nut to tighten long before a polish rod is ruined.

Just how smart a job are you doing on maintenance? How many of your leases, or even your district offices have a file of each manufacturer's recommendations regarding maintenance of his special piece of equipment? Do you have a company-wide or even a district-wide manual of standard approved practices on maintenance? Is any one man devoting a substantial part of his time to keeping track of maintenance problems, maintenance practices, maintenance costs, maintenance instruction programs?

In recent years the equipment manufacturers and their designing engineers have been coming out with a lot of new equipment. Are you personally familiar with the troublesome parts? Are you up on the manufacturer's maintenance recommendations?

If your present equipment has to last a long time with a minimum of repairs and a probable scarcity of repair parts — and that is the way the picture looks — why not make a comprehensive study of your problem now. Now is the time to get every piece of equipment in the best possible shape. Now is the time to get a comprehensive inventory of every piece of surplus equipment and every item of warehouse or tool house stock.

What looks like junk today to be thrown away or sold may look like a treasure of salvageable repair parts two years from now. If you haven't kept up lately with some of the modern repair miracles of the molten metal spraying techniques, better check up. Between molten metal spray, powdered metal techniques, and the ever increasing ingenuity of welders, you just might be amazed at what can be done to resurface a small worn surface and thereby salvage a part that in total contains a lot of steel. You can't expect your pumpers or even your district foremen

NORTH TEXAS SECTION OFFICERS for 1951 include, L to R, Earl C. Taylor, Jr., vice-chairman (Wichita Falls); Gus Athanas, vice-chairman (Fort Worth); Jack A. Crichton, chairman; K. Marshall Fagin, vice-chairman (Dallas); and Kenneth F. Anderson, secretary-treasurer. Directors not shown are W. E. Stiles, Pat Reardon, R. G. Parker, Joab B. Harrell, Jr., and Gordon R. Stine.

to keep on top of all the latest technical developments in these fields.

If your company is big enough to afford specialists you might even consider setting up a system whereby nobody is allowed to classify anything as junk until after the salvage specialist has looked it over for possible repair by some of the newer methods.

Let us sum up some ideas on maintenance. Start with the cleanest and highest standard of housekeeping you can attain. Make a complete inventory of what you have on hand now. Get everything in tip-top shape as quickly as possible. Round up every bulletin, circular, or letter on maintenance that every equipment manufacturer has ever put out. Don't forget you have a lot of ten and even 20-year-old equipment around. See to it that the foremen and pumpers who use the equipment have copies of the maintenance instructions. Get your pumpers and your foremen sold on maintenance — and having sold them the idea, give them the practical help to do the maintenance job right. Make some one man responsible for maintenance policies. Let him get thoroughly educated on the latest developments. And then give him the authority he needs to measure up to the responsibilities you load on his shoulders.

You are going to have to buy a substantial amount of new equipment for new wells on partly developed leases, and for new leases that come into production. What's the story going to be on new equipment?

For a while you're going to have more and more trouble getting equipment. Then your troubles will lessen a little bit and level off. Because this is a democracy, where we have to take human nature into account, we can predict the course of events over the next few months with fair accuracy.

First we'll have priorities and preference ratings. Since the oil industry stands high in the importance of things, you'll get pretty good ratings. But little by little, you'll find priorities and preference ratings turn out to be just hunting licenses that won't guarantee you can find the equipment you need. Finally the situation will get so bad that everyone will be willing to go on a nationwide basis to what we called in the last war the "Controlled Materials Plan." That's just polite language for direct allocation of specific amounts of critical materials to specific end uses.

When we finally get to the nationwide critical material allocation system, you will have to get a permit from the Petroleum Administration to buy anything with steel, copper, aluminum, chrome, nickel, or manganese in it. If you get a permit from the Petroleum Administration, you'll have a fair chance of getting something that will come close to doing the job. You'll get it, by wartime standards, within a reasonable time.

You will be sure of being able to do all these things if you know your way around wartime Washington or around local district offices and if your Washington contacts know how much authority the local offices have. Then there is another if. If you have someone in your organization who starts early and keeps up with all the government regulations and required forms as they develop. They'll start out as a mere trickle, then they'll grow and grow in number and volume until there will seem to be a river of them flowing across your desk every day.

Those of you who work for a major oil company won't need to worry too much about these things. Your company will have Washington experts. Your company will have headquarters staffs with men who went through the government red tape in the last war and who can quickly slip back into harness.

If you work for a small company, or you are an independent operator yourself, you've got a lot of headaches ahead of you. Your interests as a group will be well taken care of by the IPAA. I speak from experience when I say the IPAA's Washington staff is made up of very high caliber men, thoroughly acquainted with Washington's labyrinths, and highly respected. But they can represent you only as a group. Your own individual problems, in competition with all other independents and frequently with major companies will be up to you to solve.

For the smaller operators, something just might develop. We have seen a great many specialized technical services made available to small operators in the past ten years, by men going into business for themselves as consultants. If the demand exists, probably some men will set up as consultants to take on the job of steering many small operators through the jungle of wartime regulations and getting their problems put into the right channels in the Washington war agencies. Let's not have any misunderstanding. I'm not talking about men with influence — political or otherwise.

For instance, in the last war, I personally met more than one man who had come to Washington and wandered around for ten days to three weeks in the labyrinth of war agencies, military departments, etc., and never did find the right place to go get his problems handled. In all that time he never met anybody but honest men and nobody

Continued on Page 6, Section 2

The North Texas Section organized in January the North Texas Section Symposium which will be conducted in three divisions. The first, or Dallas Symposium, was held Jan. 10 under the subject of "Connate Water" and was led by W. J. McGuire of the Atlantic Refining Co. Future meetings will be held at 14-day intervals.

The second, or Fort Worth Symposium, was to be held Jan. 17. Subject was to be "Material Balance Calculations" under the direction of Gus Athanas of Stanolind Oil and Gas Co. This group will also meet at 14-day intervals.

A third group, or Wichita Falls Symposium, is still being organized and details of its program will be announced later. ★ ★ ★

EAST TEXAS SECTION

Gold and the National Economy

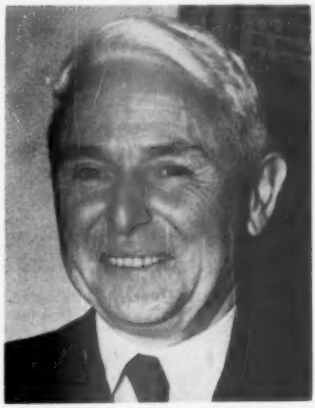
By George W. Eaton, Jr.

Donald H. McLaughlin, national president of AIME, was the guest speaker at the November 22 meeting of the East Texas Section of the AIME. The talk presented by McLaughlin urged the return of the United States and the world to the gold standard.

McLaughlin is a geologist and is president of the company which operates the Homestake Mine, the largest gold mine on the North American Continent. The speaker said the gold mining business today is so tightly controlled by a price level set in 1934 that the business is not profitable. Under the 1934 law, gold miners are required to sell all gold mined to the government at $35.00 an ounce. Therefore, the gold miner finds himself in a peculiar situation in that he is faced with a ceiling price on his product although the costs of mining gold have increased greatly.

President McLaughlin said that "inflation can be licked if the United States and the world will return to a gold standard and junk the system of paper finance, bringing a more stable balance to world trade. I doubt if we ever get back to a stable world trade until all paper money is valued on a single worldwide gold standard; then a man will know what he can expect to get paid in foreign trade. Since the end of World War I the trade of the world has been very unbalanced with the majority of the exports going from the United States. The English attempted to return to the gold standard after World War I in what is believed to be an 'honest gesture' however, they attempted to return to the gold standard on the pre-war price of gold and this did not work. The cost of war, its waste, and the resulting inflation was too great."

From time long past gold has been and remains a stable and precious metal. It is not likely that a great new discovery of a gold field will occur which would bring a marked increase in the world's gold supply. As an example, gold production in the United States has increased only 16 per cent since 1936 and we find that amount of increase inadequate to meet the demands of the population increase. The national debt is now six times greater and bank credit has increased 200 per cent since 1936. To illustrate just how scattered the world's gold deposits are, it was stated that the total gold in stock at Fort Knox is said to be worth 24 billion dollars. The total output of the Homestake Mine since its discovery has been of the order of 600 million dollars. When viewed with the light that the Homestake Mine is the largest and richest gold mine on the North American Continent, it is seen that the deposits of gold are extremely scattered.



PRES. D. H. McLAUGHLIN

As a measure for determining the correct price at which gold should be valued if the world returned to the gold standard, the speaker suggested that "we should determine the gold price on a free market for a period of three years or so. Any private citizen could own gold and do what he wants with his gold. The miner should be given the privilege of mining his gold, then either selling it to the government at the $35.00 an ounce exchange rate or keeping it. Instead of having gold pieces labeled in dollars, one ounce coins should be made and all pieces should be labeled in quantity. It would be shocking today to see the old twenty dollar gold piece and then see the new twenty dollar gold piece which would result on today's paper dollar. There would be a 50 per cent decrease in size."

The speaker stated that he believed the United States can have a more

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AUSTIN-SAN ANTONIO SUB-SECTION—Representatives of the newly-formed Austin-San Antonio Sub-Section met at the University of Texas in Austin recently in an inaugural get-together. The new sub-section was organized to bring top speakers and programs of interest to AIME members in the Central Texas area and allow more contact between student and professional members.

151 Attend Fifth Annual Texas Joint Meeting

One hundred fifty-one members, students and guests attended the Fifth Annual Meeting of Texas Local Sections in Lubbock last month to hear prominent industry men and students present papers of both general and technical interest.

Winners of the Student Paper Contest were Aubrey Brooks, Texas Technological student who took first prize of $50 with his paper "Natural Gas Dehydration;" and Richard McGannas, Texas A&M College student who won second prize with his paper, "The Use of Core Analysis in Evaluation of Secondary Recovery Operations."

Featured speaker at the joint meeting was Waldo Stephens of Oklahoma City, Okla., consultant on international affairs to the State Department. Speaking of the current world situation, Stephens offered the United States a choice of two paths to follow — go all-out militarily in Korea and simultaneously lose all of Europe to Russia or withdraw in "humiliation."

He told the AIME group that if a supreme effort were exerted by this country in Korea, Russia would release six armies poised in Europe and the western part of that continent would be overrun within 30 days.

Staff Photo

INTERNATIONAL AFFAIRS SPEAKER at the Joint Meeting of Texas Sections was Waldo Stephens, left, consultant on international affairs to the State Department. George P. Livermore is shown greeting Stephens prior to his introduction.

Earlier, Dr. D. M. Wiggins, president of Texas Tech, welcomed the attendance to the joint meeting lectures. L. T. Potter, assistant to the president of the Lone Star Gas Co., delivered a talk entitled "Teamwork Pays Dividends."

Supplementing the talk by Potter, who substituted for D. A. Hulcy, president of Lone Star Gas, was a paper entitled "Today's Natural Gas Industry" by Harold L. Hensley of Humble Oil and Refining Co. Both gas papers pointed out that the gas industry has advanced with great strides through the years with the petroleum industry.

Another session saw presented four more papers: one by Max K. Watson, natural gas consultant of Amarillo, Texas., entitled "The Future of the Engineer in the Natural Gas Industry;" another by Henry W. Hinkle of Stanolind entitled "Electric Oil Field Pumping;" a third, "Recent Progress in Scheduling Flow of Oil and Gas" by T. C. Williams, Jr., of Honolulu Oil Corp., and a fourth by James Conway of the Carl B. King Drilling Co., entitled "Mobilizing the Powers of an Organization."

The meeting was concluded with a second-day session in the Texas Tech Auditorium. William N. Little of Blackwood and Nichols Co., Midland, Tex., and Phillip Johnson of Texas Tech were associate chairmen. Papers given were "Training an Engineer in the Drilling Industry," by David B. Schulz of George P. Livermore, Inc.; "Modern Developments in High Pressure Pipe." by George A. Whetstone of Texas Tech's civil engineering department; and "Factors Affecting Primary Cementing of Casing in Rotary Drilled Holes," by Waldo L. Grossman of Halliburton Oil Well Cementing Co., Midland. ★ ★ ★

Staff Photo

AWARD WINNERS at the Fifth Annual Joint Meeting of Texas Local Sections held last month at Texas Technological College in Lubbock were Aubrey Brooks, left, and R. L. McGannas. Brooks won $50 with his paper, "Natural Gas Dehydration." McGannas took second place with his paper, "The Use of Core Analysis in Evaluation of Secondary Recovery."

PACIFIC TECHNOLOGY GROUP

Aspects of California Water Flooding

By N. van Wingen

The eighth lecture of the current AIME series on Secondary Recovery was given by Robert Hawkins of Fullerton Oil Co. on November 27, 1950, at the General Petroleum Auditorium in Los Angeles.

Hawkins expressed the opinion that because California sands are in general very thick, water flooding should be accomplished by intervals which probably should not exceed 50 feet. While generally sedimentary anomalies will exist to make such subdivision of zones practically feasible the possibility of artificially plugging to accomplish subzonal segregation is also to be considered. By taking small portions of a thick zone at a time for flooding it is obviously much easier to control water by-passing.

The fact that California sands do not require shooting is a distinct advantage in that pipe can, under these circumstances, be run and gun perforated selectively. A disadvantage for California sands to water flooding is their mineral content which often is of critical importance. Not only will clay hydration, when it occurs cause reduction of permeability, but the sand grains themselves may change as they come in contact with the invasion water to the point that they will become preferentially oil-wet. Proper treatment of the injection water may prevent or at least minimize such zonal damage.

Of the sand's physical characteristics, grain size, degree of cementation, shape factor and tortuosity are more important than the simple values of porosity and permeability in determining its adaptability to successful flooding. With regard to the fluids contained within the sand, the per cent oil and water saturation, the viscosity of the oil and the presence of impurities which may precipitate in the course of flooding are the most important factors to be considered.

To ascertain the prospective flood value of a property the best results can be obtained by means of laboratory flood pot tests. In order that these may give representative results it is very important that essentially uncontaminated core samples are obtained. Though special equipment such as a pressure core barrel can be used to this end, better results have been obtained in California by using a diamond core head and an oil base drilling fluid. Barren sands up to a permeability of 1,200 md were found to have a $\frac{3}{4}$-in. invasion while lower permeability oil sands were penetrated only to the extent of $\frac{1}{8}$ to $\frac{1}{4}$ in. In addition it has been possible by means of diamond coring to obtain 100 per cent core recovery. ★ ★ ★

ROBERT HAWKINS

SOUTHWEST TEXAS SECTION OFFICERS — Newly elected officers for 1951 who will govern the Southwest Texas Section are, L to R, Francis Hebert of Wilson Supply Co., director; C. L. Wheless of La Gloria Corp., director; Henry Kerr of Taylor Refining Co., director; C. W. Kelley of Fair-Woodward Corp., director; H. D. Vaughan of Lane-Wells Co., secretary-treasurer; Frank Saye of Halliburton Oil Well Cementing Co., director; and L. J. Thronson of Sun Oil Co., chairman.

Additions to New 1951 Directory

The geographical directory for South Carolina was omitted unintentionally from page 398 of the current Directory for 1950. The omissions are listed below and may be clipped by those interested in completing their new directory.

Anchor Corp.:
  St. George:
    Lauer, F. C., Acct.
Commercialores Inc.:
  Clover:
    Beers, S. J.
    Karchmer, N. K., V.P.
West Virginia Pulp & Paper Co.:
  Charleston:
    Keilen, Jr., J. J.
Zonolite Co.:
  Travelers Rest:
    Johnson, Jr., H. S.
    Stewart, O. F.
Miscellaneous
  Abbeville: Welhaven, A.
  Anderson: Brown, C. M.
  Charleston: Taylor, R.
  Columbia: Buie, B. F.; Taber, S.*
  Greenville: Kelly, J. A.
  Rock Hill: Emlow, H. S. ★ ★ ★

Studying Microscopic Pore Channels with Photography

By J. C. McCarthy

R. A. Morse of Stanolind Oil and Gas Co. presented a brief introductory discussion at the Mid-Continent Section's Dec. 11 meeting, telling how the magic of color motion pictures can be used to dispel some of the mysteries surrounding the flow of oil, gas, and water through microscopic pore channels in reservoir rocks.

Many of the problems of efficiently producing more oil and gas cannot be solved until engineers have a better knowledge of how and where fluids occur in the pores of the petroleum reservoirs. Because these pores are often invisible to the naked eye, special techniques have been devised with the objective of seeing and recording the behavior of fluids inside pores. Studies of this nature are directed toward giving engineers a better understanding of the mechanics of flow in oil reservoirs.

Two visual laboratory studies of this kind are being conducted and progress reports of each of them were presented at the meeting. Both of these investigations were presented in the form of colored motion pictures; one by the Pennsylvania State College for work done under the auspices of the South Penn Oil Co.; the other by the University of Oklahoma on work done under the auspices of the API Project 47-B.

Morse briefly discussed the research being performed at Penn State and the film entitled "Microscopic Studies of Capillary Flow" was then shown. This film was accompanied by a sound track, giving a commentary with the pictures. The porous systems used were sand grains fused inside of glass capillary tubing. Oil, water, and gas were forced through these systems and the shape of the interfaces during flow was photographed through a microscope lens. The manner in which residual oil was trapped in the pores after water flooding could be seen. Other studies were made on the flow of fluids in a clean glass capillary tube. These showed that oil left as a film on the tube walls after displacement with gas was removed by a subsequent water drive.

Work under API Project 47-B was presented by means of colored moving pictures with a running commentary given by Alfred Chatenever. The porous systems used in this study were single layers of spherical grains (.007 in. in diameter) placed between two flat sheets of transparent material. Cells studied were made either completely of glass, completely of lucite, or of a combination of the two materials. Significant observations made during the flow of crude oil and water either individually or together through these cells are as follows:

(1) Each fluid flows in its own separate channel, forming a winding network through the porous system.

(2) At very high rates of flow of both oil and water, the fluids flow not in continuous networks, but rather in slugs.

(3) There was visual evidence that residual oil bubbles, although they do not flow through the porous system, do rotate as water passes by them.

(4) In an all-glass system, connate water was observed to be concentrated as rings around the contact of the sand grains. This did not hold true for all-lucite systems.

(5) In an all-glass system, residual oil was observed as globules located between sand grains.

Observations made of the total porous cell showed that when water flooded oil, the displacement mechanism took the form of fingers of water through the oil, but when oil displaced water, the flood front appeared to have a more regular pattern. The projects reported on at this meeting are not completed and work is still continuing. ★ ★ ★

J. M. Moore Elected Permian Basin Chairman

New officers of the Permian Basin Section were elected November 25 at Midland. They are: J. M. (Jack) Moore, Midland, chairman; Joe Chastain, Midland, vice-chairman; Ray Ousterhout, Odessa, secretary-treasurer.

W. N. (Bill) Little, Midland, is the retiring chairman while Ray E. Howard, Midland, is retiring vice-chairman and Chastain retiring secretary-treasurer. The new officers will assume their duties at the first meeting in 1951.

Dr. Donald Hamilton McLaughlin, AIME president, made his official visit at the November meeting. Dr. McLaughlin's speech was divided into three parts. First he discussed the need for a stable, gold-backed currency; next, the mineral policy of the United States, and last the work and aims of the Institute. ★ ★ ★

J. M. MOORE

Kansas Officers

G. L. Yates of Amstutz and Yates of Wichita, Kans., was elected chairman for 1951 of the Kansas Section at its December meeting in Wichita. Other officers elected include T. J. Hamilton of Wichita, L. W. Holsapple of Augusta, Kans., and J. C. Gallivan of Great Bend, Kans., vice-chairmen; E. L. Auders of Lawrence, Kans., and J. R. Berg of Wichita, directors; and George J. Decker, secretary-treasurer.

PETROLEUM BRANCH PROGRAM

AIME ANNUAL MEETING IN ST. LOUIS

February 17-22, 1951

Because St. Louis is centrally located in several important oil producing areas, and consequently accessible to a large number of Petroleum Branch members, a special Petroleum Branch program has been arranged for the forthcoming AIME Annual Meeting. The program has been diversified to appeal to a wide segment of the membership, with special emphasis placed on the Illinois Basin area. Bob Diggs Brown of Halliburton Oil Well Cementing Co. in Flora, Ill., has served as program chairman for the meeting, and is due the thanks of the membership for arranging the excellent program outlined below.

All AIME members are especially invited to attend the meeting, and guests will be very welcome. Hotel accommodations should be arranged through: Hotels Convention Reservation Bureau, 911 Locust Street, St. Louis. All Petroleum Branch functions will be held at the Statler Hotel.

Members of the Illinois Basin Chapter of the Petroleum Branch will be hosts to the Branch at the meeting. William B. Berwald of the Ohio Oil Co. in Findley, Ohio, is Petroleum Branch General Chairman for the meeting.

SATURDAY, FEBRUARY 17

Meeting of Section Delegates, all AIME Local Sections

SUNDAY, FEBRUARY 18

Meeting of the AIME Board of Directors

MONDAY, FEBRUARY 19

9:00 - 11:45 a.m. **St. Louis Room** **Statler Hotel**

OPEN MEETING, PETROLEUM BRANCH EXECUTIVE COMMITTEE

Petroleum Branch Chairman, Presiding

12:15 p.m. AIME Welcoming Luncheon

2:15 - 5:00 p.m. **St. Louis Room** **Statler Hotel**

CLOSED EXECUTIVE SESSION, PETROLEUM BRANCH EXECUTIVE COMMITTEE

Petroleum Branch Chairman, Presiding

7:00 p.m. AIME Dinner - Smoker

TUESDAY, FEBRUARY 20

8:30 - 11:30 a.m. **St. Louis Room** **Statler Hotel**

Production Review Session: WORLD OIL AND GAS DEVELOPMENTS DURING 1950

Presented by the 1950 and 1951 Production Review Committees

D. V. Carter, 1950 Chairman and E. W. Berlin, 1951 Chairman, Presiding

Foreign Vice-Chairman: Alexander H. Chapman, Arabian American Oil Co., New York

Domestic Vice-Chairman: R. B. Gilmore, De Golyer & MacNaughton

Committee Members:

Lawrence W. Chasteen, Union Oil of California
Gerald E. Eddy, Michigan Department of Con.
Gordon H. Fisher, Gulf Oil Corp.
Raymond M. Larsen, U. S. Geological Survey
John A. Murphy, Continental Oil Co.
Milton Williams, Humble Oil and Refining Co.
John K. Wright, Jr., Miss. State Oil and Gas Board

This session consists of brief reviews of world-wide developments and production highlights of 1950. Presentation will be by the above members of the committee or their alternates.

TUESDAY, FEBRUARY 20

2:15 - 5:00 p.m. **St. Louis Room** **Statler Hotel**

Technical Session: WATER FLOODING IN THE ILLINOIS BASIN

Bob Diggs Brown and L. W. Swanbeck, Presiding

101-G: "Water Flooding in the Illinois Basin Area Yesterday, Today and Tomorrow," by H. S. Barger, Consultant.

2:15 - 3:05, Presentation and Discussion

Industry-wide interest is being shown in water flooding in the Illinois Basin Area. A review of the water flooding history shows that there has been a marked degree of success and that many of the reservoirs in the area are adaptable to water flooding.

Several large water flood projects are in operation at present and several are in the formative stage. Possibly the largest water flood project in the industry is located in the Basin area and will be fully subjected to water flooding within the next few months. A wider application with earlier and more efficient water injection is foremost in the operators' thinking for tomorrow.

102-G: "The Benton Water Flood, Franklin County, Illinois," by C. V. Cameron, Shell Oil Co. (Tentative)

3:05 - 4:10, Presentation and Discussion

This paper is a review of the operation of the Benton water flood project during its first year, and an outline of reservoir characteristics. The operation is a fully unitized project covering about 1,900 productive acres, and water is injected into the Tar Springs sandstone reservoir at a depth of 2,100 ft. The project was started in November, 1949.

103-G: "The General Aspects, Engineering and Operational, of the Formation of the Salem Unit," by Richard W. Love, The Texas Co.

4:10 - 5:00, Presentation and Discussion

This paper presents the background of the Lake Centralia - Salem Field, its history and possible future. The material deals with actual formation of the Unit which represents the result of two years' work on the part of some 28 operators along with the concurrence of approximately 1,950 royalty owners, and gives the background of the field.

The work of the Steering, Engineering, Legal, Land and Accounting Committees is given in detail along with their conclusions and results to date.

TUESDAY, FEBRUARY 20

6:00 p.m. **St. Louis Room** **Statler Hotel**

PETROLEUM BRANCH ANNUAL BANQUET

(Ladies invited. Dress, informal for men; ladies optional)

Installation of Petroleum Branch Officers for 1951

The principal speaker will present an address of interest to the petroleum industry.

(Over)

WEDNESDAY, FEBRUARY 21

9:15 - 11:45 a.m. **St. Louis Room** **Statler Hotel**

Technical Session: DRILLING, LOGGING AND ACIDIZING

Cecil A. Hamman and B. A. Barnes, Presiding

104-G: "An Analysis and the Control of Lost Circulation," by George C. Howard and P. P. Scott, Jr., Stanolind Oil and Gas Co.

Formation fractures are frequently the cause of loss of circulation. Those that are created or widened by fluid pressures have been recognized as the most difficult to seal. A study of the variables which are related to fracturing led to the belief that the presence of an effective lost circulation material in the mud stream might serve to plug small fractures at the moment of their occurrence and thereby prevent fluid pressures from widening and extending the fractures and causing lost circulation.

A large number of lost circulation materials were classified and tested in simulated fractures and in shallow wells. A new type of centrifugal sorter was given preliminary tests and found to be apparently capable of separating lost circulation materials and cuttings.

105-G: "The Laterolog: A New Resistivity Logging Method with Electrodes Using an Automatic Focusing System," by H. G. Doll, Schlumberger Well Surveying Corp.

10:05 - 10:55, Presentation and Discussion

A new electrical logging method called Laterolog is described which provides for better recording of formation resistivity. In this method a current, preferably of constant intensity, is forced into the formation perpendicularly to the wall of the hole as a sheet of predetermined thickness by means of a special electrode arrangement and of an automatic control system.

The essential advantages of the Laterolog over the regular resistivity logs are explained.

Field examples are shown to illustrate the results of the method in various types of formations.

106-G: "Improvement of the Acidizing Process by the Formation of Channels," by P. H. Cardwell, Dowell Incorporated.

10:55 - 11:45, Presentation and Discussion

A recent development in the acidizing of oil wells is the use of agents in the acid to bring about the phenomena of dissolving small channels for considerable distances into the formation. This is accomplished by the use in the acid solution of organic film-forming, gellifying agents. The presence of such agents results in practically all of the acid being consumed in the formation of small channels and only small amounts of the acid reacts with the face of the well bore or other non-desirable sections of the formation.

The paper, besides giving the theory as to how the acid forms channels, gives the treating technique used for carrying out the treatments and also lists the results of actual field treatments.

WEDNESDAY, FEBRUARY 21

2:15 - 5:00 p.m. **St. Louis Room** **Statler Hotel**

Technical Session: RESERVOIR AND PRODUCTION ENGINEERING

J. R. Vaughan, Jr. and W. F. Brown, Presiding

107-G: "An Experimental and Theoretical Investigation of Gravity Drainage Performance," by P. L. Terwilliger, Howard N. Hall, L. E. Wilsey, P. M. Bridges, and R. A. Morse, Stanolind Oil and Gas Co.

2:15 - 3:00, Presentation and Discussion

For a system where pressure is maintained above the bubble point, experimental data are presented indicating that from a recovery standpoint there is no particular significance to the "maximum rate of gravity drainage." Refined methods of solution of frontal drive problems have been developed for allowing calculation of detailed saturation distribution during replacement. Excellent agreement between experimental and calculated behavior is obtained.

108-G: "Measuring the Water Vapor Content of Gases Dehydrated by Triethylene Glycol," by Irwin Politziner, F. M. Townsend and L. S. Reid, University of Oklahoma.

3:00 - 3:45, Presentation and Discussion

Recently published data[1] indicate that the water vapor content of a gas, determined by dew point measurement, is inaccurate when the gas has been treated, or dehydrated, with diethylene glycol. Water vapor contents and dew point measurements of gases dehydrated with triethylene glycol have been obtained in this investigation in order to determine the magnitude of a similar error, if one exists.

Experimental data show a very low concentration of triethylene glycol vapor in gases dehydrated at atmospheric temperatures and pressures ranging from 500 to 2500 psia, and that the accuracy of dew point measurements is not impaired by the presence of this glycol vapor.

[1]Riesenfeld and Frazier, *... and G. J.*, 48, 12, 238, July 28, 1949.

109-G: "Design and Performance of Horizontal Separators for High Rates of Production," by E. J. Lyon and E. Van Dornick, Arabian American Oil Co.

3:45 - 4:20, Presentation and Discussion

Reasons are given for the design and operation of horizontal gas-oil separators for high production rates. Results of full scale experimental models which were used as the basis for present design, and factors influencing design are listed. Operations of five 100,000 B/D horizontal separator plants in the Abqaiq Field of the Arabian American Oil Co. are described and economic comparisons of horizontal and vertical separators for high rates of production are made.

110-G: A Petroleum Engineering Progress Report on the Scurry County, Texas, Reef Field, by William L. Horner, Sunray Oil Corp.

4:20 - 5:00, Presentation and Discussion

This paper describes the Scurry County Reef Field geologically, presents the performance data and describes the reservoir and its fluid contents. Operating aspects and plans are reviewed.

7:00 p.m. **Annual AIME President's Reception and Banquet**

DISCUSSION OF THIS AND ALL FOLLOWING TECHNICAL PAPERS IS INVITED
Discussion in writing (3 copies) may be sent to the Editor, *Journal of Petroleum Technology*, 601 Continental Building, Dallas 1, Texas, and will be considered for publication in the Transactions volume *Petroleum Development and Technology*. Discussion will close December 1, 1951. Any discussion offered thereafter should be in the form of a new paper.

AN INVESTIGATION OF THE ELECTROKINETIC COMPONENT OF THE SELF POTENTIAL CURVE

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ABSTRACT

Eight laboratory-prepared aqueous base drilling muds representing common mud types, and 15 aqueous base drilling muds sampled in the field, have been used in an experimental investigation of the relationship between the streaming potential developed across a mud filter cake and the differential pressure causing filtrate flow.

It has been established that the relationship is of the form, $E_s = kP^y$, where E_s is the streaming potential, P the differential pressure and k and y are constants for any particular mud system at constant temperature. Beyond a certain minimum thickness this relationship is independent of filter cake thickness. Experiment has shown that both k and y are temperature dependent parameters and that in certain mud systems there is a critical value of P above which the simple relationship $E_s = kP^y$ ceases to hold. The constant k tends to be a function of the mud resistivity at 77°F, but the exponent y has not been found to be related to any commonly measured mud property.

Certain field experiments are described which serve to demonstrate that the total SP (self potential) developed opposite a formation may be quantitatively accounted for as the algebraic sum of an electrochemical potential and an electrokinetic potential. A chart to permit the simple use of mean solution activities in the interpretation of electrochemical SP data is given and its use described.

Various field methods for computing the electrokinetic SP component of the total SP are considered and rejected as being unduly complicated and inaccurate. It is shown that the employment of low resistivity drilling muds is essential if optimum accuracy is desired in the use of the S.P. curve for the purpose of computing connate water salinities by the electrochemical SP method. The use of such low resistivity drilling muds is accordingly recommended.

INTRODUCTION

In a previous paper[1] a quantitative analysis of the electrochemical component of the SP (self potential) curve was made and it was shown that the electrochemical* emf, E, could be expressed as $E = 2\bar{\imath}RT/F \ln a_c/a_m$, where $\bar{\imath}$ is the transference number of the chloride ion, R is the gas constant, T the absolute temperature of the formation water and mud, a_c the mean activity of the connate water (assumed to be sodium chloride) and a_m the mean activity of the mud (as sodium chloride). The essential accuracy of this expression was confirmed by an investigation[2] of the SP kicks opposite sands of known water salinity. The logs examined had been routine runs in oil wells in a number of Mid-Continent states. Further confirmation of the original analysis of the electrochemical SP is implicit in the paper by Tixier[3] wherein a relationship between the SP and the ratio of connate water and mud resistivities, based only on field data, is given. Allowing for the fact that mud and connate water resistivities were used instead of activities, and that electrokinetic effects were ignored, the constant reported by Tixier is essentially $2\bar{\imath}RT/F$.

The error involved in the universal substitution of resistivities for activities will receive further reference below. Possible reasons for the fact that the electrochemical properties of shales do not appear to be significantly dependent upon either the nature or the quantity of cation exchange materials, such as clays, they contain has been considered at some length by Wyllie and Patnode.[4] In the same paper, the probable effects of shale thickness and compaction on electrochemical efficiency, and hence the inherent difficulty of obtaining reliable laboratory-scale data, were also pointed out. However, it is

[1]References given at end of paper.

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*It seems desirable to make specific reference to the effect of pressures and temperatures on electrochemical reactions since the effect of pressure, particularly, seems to be either ignored or confused.[5] The effect of pressure is only marked in those electrochemical reactions involving gases e.g. H_2 gas electrode. Otherwise, the effects are dependent upon volume changes which are negligibly small at the pressures involved in drilling. The effect of pressure on resistivities depends upon concentration of the solute, but generally does not exceed ±5 per cent.[7] The effect of pressure on activities is discussed by Robinson and Harned[8] and is shown to be very small e.g. for *NaCl* the activity coefficient is only 5 per cent greater at 15,000 psi than at atmospheric pressure. Similarly, Robinson and Harned show that the effect of temperature on activity can be neglected from the logging standpoint.

clear both from a theoretical consideration of the energies involved and from the detailed analysis of the potential and current distributions in a borehole made by Doll[5] that log-recorded electrochemical potentials should be, at best, only asymptotic to the theoretical values.

Thus, from the thermodynamical standpoint, the energy available for release and manifestation as an electromotive force is dependent upon the difference in chemical potential between the mud fluid and connate water. Irrespective of the mechanism whereby the electrochemical potential is set up, this chemical potential difference defines the maximum emf of the cell, and this emf will in turn be measurable at its maximum value only under conditions of no current flow and thus no internal ohmic potential drops in the electrochemical cell.

Such a measurement may be achieved in the laboratory by balancing the cell emf against an equal and opposite emf by the use of a potentiometer. In the field, however, the normal method of logging the SP is contingent upon current flowing in the borehole, and the fact that this must always preclude precise agreement between the measured SP and the actual emf of the electrochemical cell has been fully discussed by Doll.[5] However, under conditions of adequate bed thickness and low bed resistivities, the difference between the measured and theoretical emf's is neglibly small. The recently described Selective SP logging technique[16] may also serve to facilitate quantitative SP calculations by rendering formation geometry less important as a factor affecting the magnitude of the recorded SP. The presence of shale in the formation, which may be considered as an extreme example of the thin bed difficulty, also serves to lower the measured SP below the true value of the emf causing current flow. Thus, it may be said, that while there is a number of reasons to explain log-recorded SP values which are less than the theoretical electrochemical emf's, any errors which are markedly in the opposite sense and which exceed any reasonable errors resulting from errors in the determination of the appropriate mud and connate water activities must betoken the existence of an additional potential. Such marked positive errors* have been observed in tests of the efficacy of the SP method of determining connate water resistivity, particularly striking examples of this effect being noted[2] in the case of the McClosky producing zone in Illinois where the SP was some 40 mv larger than anticipated. The possibility that electrokinetic or streaming potentials were sometimes of greater importance than had been first believed was therefore considered, and experiments to investigate the phenomenon were undertaken.

NATURE AND LOCATION OF ELECTROKINETIC POTENTIALS

Electrokinetic effects of all types result when there is relative movement between a solid and a liquid. The effects are generally ascribed to the fact that there is a potential difference at the solid/liquid interface at which movement occurs, this potential being known as the zeta potential. If this zeta potential results from the presence of electrically-charged layers opposite in sign at the surface of separation of the solid and the liquid, then the application of a pressure which causes movement of the liquid past the solid must result also in the movement of a charge past the solid surface. Such a charge movement represents the flow of current and a potential is immediately set up of a magnitude which follows Ohm's Law. Numerically this streaming potential, as it is called, may be calculated if both the rate and magnitude of the charge moved and the overall resistance of the system are calculable. Since the phenomenon is ultimately dependent upon the magnitude of the zeta potential, a quantity which cannot be theoretically calculated, it has been usual to measure streaming potentials in systems of sufficient simplicity to enable all variables other than the zeta potential to be independently measured, and thus to compute the zeta potential itself. For simple systems and particularly those for which the hydraulic and electrical paths are identical, it has been established that the streaming potential is directly proportional to the pressure causing flow. For any particular zeta potential the streaming potential is also directly proportional to the resistivity of the liquid being flowed (neglecting surface conductance effects and assuming that the solid material past which the liquid flows is a non-conductor). However, since the zeta potential is itself a complex function of the solute concentration and hence the resistivity of the liquid flowing, no extrapolation of the streaming potentials determined for solutions of one resistivity can be made even to solutions of identical chemical nature but of different resistivity.

The fact that the movement of an electrolyte through a solid such as a capillary tube or a more complex system such as an aggregate of sand grains or a fritted diaphragm gave rise to a potential had been noted by C. and M. Schlumberger and E. G. Leonardon,[5] and in their pioneer work on electric logging they first ascribed the SP solely to such electrokinetic effects. In a later paper[10] the same workers modified their original view and the SP was attributed to a combination of electrokinetic and electrochemical effects. Thus, it would appear that at a very early date the principle components of the "SP" curve had been correctly elucidated. Published investigations of streaming potential phenomena involved in electrical logging are meager but are most extensive for the electrokinetic phenomena obtaining in the logging of cable-tool drilled wells. Since the seat of the major electrokinetic effects appear to be entirely different in rotary-drilled and cable-tool drilled wells, it will suffice to say here that Gillingham[11] in an investigation of the effect of varying the borehole fluid pressure in cable tool wells in Pennsylvania and New York State, found that the ordinary negative SP became more negative when the borehole pressure was increased. More recent analogous experiments by Pirson[12] in the Bradford field gave similar results except that both increased and decreased SP kicks were observed to result from increasing the differential pressure between the borehole fluid and the formations. These latter results point to the existence of positive and negative zeta potentials and not to a consistent negative zeta potential (i.e., solid surface negatively charged with respect to water) as found by Gillingham.

The fact that a deliberate increase in borehole mud pressure in the logging of a conventional rotary-drilled well tends to increase the magnitude of the usual negative SP kick is well-known and has been remarked upon in the literature.[6,13] The location of the streaming potential in a rotary-drilled well in which the formations have been mudded-off with an appreciable thickness of filter cake is not, however, the same as that in a cable-tool drilled well where the formation faces are unprotected by a relatively impervious mud cake. In the latter case, the pressure differential between the hydrostatic pressure of the mud in the hole and the formation pressure results directly in movement of borehole fluid into the formation.

In addition, although not invariably true, the resistivity of the water used in cable-tool well experiments is much higher than the resistivity of high-resistivity rotary drilling muds. The

*Positive in terms of numerical value. Note that the sign of the SP is generally negative.

consequence is that the streaming potential is set-up principally by the flow of the high resistivity borehole fluid through the pores of the formation rock matrix and the magnitude of this potential is a function of the zeta potential between the moving borehole fluid and the rock surface. Thus, the streaming potential may here be said to be somewhat dependent upon the nature of the formation solids. In addition, the high resistivity of the flowing borehole fluid contributes to a large streaming potential since, as noted above, by Ohm's Law the streaming potential, for any value of the zeta potential, is directly proportional to the resistivity of the fluid flowing.

In a rotary-drilled well mudded-off by a mud filter cake, very different conditions obtain. Here the permeability of the filter cake may be only 10^{-2} md, whereas the permeability of the formation, if of commercial interest, is unlikely to be less than 10 md. In consequence, by far the greatest pressure drop between the hydrostatic pressure of the borehole mud column and the formation pressure occurs across the filter cake, less than 1 per cent of the drop occurring between the formation face of the filter cake and the formation itself. The consequence of this pressure distribution is that the major portion of any streaming potentials occurring in a rotary-drilled well, since they are a function of pressure distribution, must occur across the mud filter cake, any streaming potential component occurring in the formation rock matrix itself being negligible by comparison. A similar conclusion appears to have been reached by Mounce and Rust,[6] by Doll[13] and, originally, by Bayle[14] in 1935. Thus, in rotary-drilled wells, the streaming potential will be predominantly a function of the properties of the drilling mud and its filter cake and not of the formations.

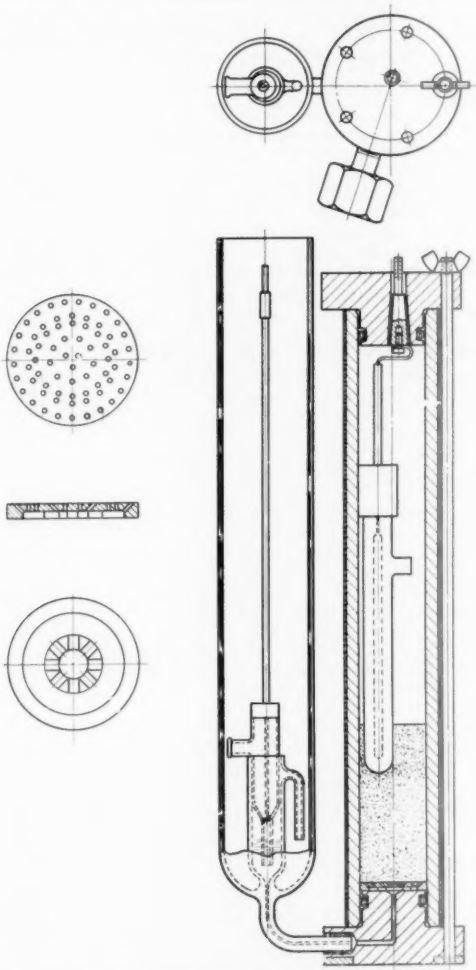

FIG. 1 — CROSS-SECTION OF STREAMING POTENTIAL CELL SHOWING ARRANGEMENT OF CALOMEL ELECTRODES.

The only previous experimental measurement of the streaming potential resulting from the flow of a mud filtrate through its own filter cake appears to have been carried out by Mounce and Rust[6] who observed, for what was described as a typical drilling mud, a 20 mv streaming potential for a 200 psi differential pressure between the mud and its filtrate.

EXPERIMENTAL

Apparatus

The final apparatus developed is shown in its high-temperature form in Fig. 1. Basically the apparatus consists of a 10½-in. long Nylon cylinder of a 3/16-in. wall thickness and a 1-in. internal diameter. To overcome high-temperature creep this cylinder is a tight fit in a 1/16-in. thick cylindrical steel jacket. The lower end of the cylinder is closed by a flanged Lucite plug, pressure tightness being ensured by the use of a neoprene "O"-ring. The Lucite plug is drilled with 1/16-in. diameter holes in the vertical and horizontal directions as shown in Fig. 1 to permit flow of mud filtrate through the Lucite plug and external glass capillary tube into the jacketed external glass-filtrate reservoir. The glass-capillary tube is retained in the plug by the aid of a tygon gasket. Within the cylinder and resting on the Lucite plug is an asbestos-base Bakelite filter disc. The construction of this disc is shown in a detail in Fig. 1.

The top of the cylinder is closed by a flanged stainless steel plug, pressure tightness again being achieved by the use of a neoprene "O"-ring. Through the top of the stainless steel plug passes a conical stainless steel pin insulated from the plug by means of a Nylon sleeve. To the lower end of this pin is soldered a connection to a 5-in. Beckman calomel electrode incorporating an asbestos-wick slow potassium chloride leak. The tip of the electrode is arranged to be about 2-in. from the filter disc when the apparatus is assembled. The terminal connection at the outer end of the Nylon insulated pin is connected to the potential measuring equipment. In addition to the electrode connection, the stainless steel plug may be connected through standard pipe fittings to a source of high-pressure gas.

In routine operation the lower Lucite plug is inserted in the cylinder and a disc of Whatman No. 42 filter paper is placed over the filter disc. About 3 to 4 in. of mud is then poured into the cylinder and the upper plug with attached electrode is inserted into the top of the cylinder. The protective rubber stopper over the side arm of the calomel electrode may conveniently be perforated with a small hole and left in place.

The flanges of the upper and lower plugs are then pulled together by the tightening action of five wingnuts threaded on stainless steel rods.

A 2-in. Beckman calomel electrode with asbestos leak is lowered into the jacketed filtrate reservoir and the capillary tube with its tygon gasket pressed into the Lucite plug. This electrode is also connected to the potential measuring apparatus, consisting of a Leeds and Northrup Type *K* potentiometer and Leeds and Northrup thermionic amplifier No. 7673. The accuracy of this equipment is about ±0.1 mv.

Pressure is then applied by means of nitrogen gas to the space above the mud in the cylinder, provision being made in the gas line both for the regulation and for the measurement, by means of a calibrated 6-in. diameter 0 - 500 psig, of the pressure applied.

In high-temperature experiments the mud was warmed to approximately the correct temperature before insertion into the cylinder and the entire apparatus was lowered into a water bath thermostatically maintained within ±0.2°C of the required temperature.

For room-temperature experiments it was found to be more convenient to replace the steel-jacketed Nylon cylinder with a transparent Lucite cylinder of ¼-in. wall thickness. The outer jacket of the external glass filtrate reservoir was also dispensed with in these experiments.

While the general construction of the equipment and the reasons for the design adopted is straightforward, certain features deserve amplification. The final choice of calomel electrodes was only made after extensive tests of silver/silver chloride, lead/lead chloride and inert platinum electrodes had been made. The silver/silver chloride and lead/lead chloride electrodes, although workable in some cases, were found to be undesirably unstable. This is almost certainly a consequence of the heterogeneous nature of drilling muds and the resultant presence in solution of anions in addition to the chloride ion to which alone these electrodes are reversible. The fact that many muds are active oxidation-reduction systems made the use of inert electrodes impossible, the varying redox potentials in the mud and filtrate being superimposed on the streaming potential and leading to a prohibitive instability of the electrode zero.

The insertion of a calomel electrode with a slow-leak type saturated potassium chloride junction within the high-pressure cylinder has a number of advantages. No complex liquid connection leading from cylinder pressures of up to 500 psig to atmospheric is required and for obvious reasons the pressure causing potassium chloride leak into the mud remains merely the hydrostatic head of the potassium chloride solution within the electrode itself. This leak is almost negligible and contamination effects on the mud during the course of an experiment were not measurable. If the potential of the calomel electrode were a sensitive function of pressure, changes of potential caused by pressure would, of course, be algebraically added to the measured streaming potentials. However, the pressure dependence of the potential of a saturated potassium chloride calomel electrode is of the order of microvolts per atmosphere and can be neglected.

The use of the asbestos-base Bakelite filter disc to support the filtering medium employed was to avoid the presence of any metal in the system. As will be shown below, the geometry of the filtering medium does not appear to have any significant effect on the results obtained. The volume of the filtrate path from filter cake to external calomel electrode was kept to a minimum in order to complete the electrical circuit before a large volume of filter cake built-up. This design necessitated the use of a glass-capillary tube which might be considered objectionable as a possible source of streaming potential in series with any streaming effects across the mud filter cake itself. In practice, however, the rate of flow through this capillary tube is so slow, and the resistivity of the filtrates relatively so low, that no detectable streaming potentials exist.

Muds

It may justly be claimed that no two drilling muds are ever identical, and although this does not mean that modern muds cannot be roughly grouped according to their principal components and chemical additives, it does necessarily render rather difficult the choice of suitable muds for any limited series of experiments intended to obtain results of general applicability. With this in mind the following arbitrary selection was made. Eight muds were made for the writer by the mud section of Gulf Research and Development Co.'s Materials and Production Chemistry Division. These muds, although relatively artificial, covered a wide range of types and their preparation is given in detail in the Appendix. In addition, a number of other muds were obtained during routine field drilling operations. These latter muds were sampled at the flow nipple while the mud was being circulated prior to electric logging. The samples were hermetically sealed in cans or bottles and dispatched to the laboratory. In one instance, five mud samples were obtained at depths of 1,300 ft, 2,375 ft, 4,295 ft, 5,600 ft and 5,812 ft in the same well in order that an estimate of the changes occurring during drilling with the same basic type of mud could be studied. In all 15 different field muds from various geographical areas in the United States and abroad were available and were tested. The range covered by the laboratory and field samples included, in addition to more standard types, a silicate mud and two oil-emulsion muds. Details of the conventional mud properties of all the samples studied, including resistivities, are given in Tables I and II, as well as their common, if somewhat uninformative, field descriptions.

Table I

No.	Type of Mud	Weight lb/gal	pH	Viscosity cp.	GEL STRENGTH Initial gms.	GEL STRENGTH 10-min. gms.	CAKE PROPERTIES 30-min. ml.	CAKE PROPERTIES Cake ins.	RESISTIVITIES 64°F ohm-m.	RESISTIVITIES Test Temp. ohm-m.	Slope	Intercept mv	E_0 for 500 psi
1	3% Starch in high pH mud	8.64	10.7	95.9	4	60	4.0	1/32	6.6	5.8	0.63	0.45	22.5
2	Fresh water clay	9.76	8.3	17.0	0	28	12.4	1/32	7.0	5.9	0.57	0.93	31.0
3	Oil emulsion	10.11	9.1	61.0	0	1	5.6	2/32	3.3	2.9	0.88*	0.125	20.5
4	Oil emulsion + 2% NaCl	10.0	8.3	101.0	81	81	11.1	2/32	0.6	0.52	0.78	0.05	6.5
5	Red lime mud	14.6	12.0	52.5	0	48	28.4	5/32	0.32	0.27	0.83	0.046	8.0
6	Saturated salt water mud	13.75	6.4	50.9	5	36	3.4	1/32	0.08	0.07	0.66	0.017	1.05
7	6% bentonite in distilled water	8.7	8.6	42.7	1	36	13.1	2/32	6.6	5.3	0.70**	0.80	28.0
8	6% Zeogel in 30% NaCl solution	10.1	7.1	10.0	0	0	60.0	5/32	0.06	0.05	0.74	0.01	1.0

*to 140 psi
**to 100 psi

Table II

No.	Type of Mud	Weight lb/gal	pH	Viscosity cp.	GEL STRENGTH Initial gms.	GEL STRENGTH 10-min. gms.	CAKE PROPERTIES 30-min. ml.	CAKE PROPERTIES Cake ins.	RESISTIVITIES 64°F ohm-m.	RESISTIVITIES Test Temp. ohm-m.	Slope	Intercept mv	E_s for 500 psi
9	Caustic quebracho, New Mexico	9.9	8.3	18.6	0	16	19.0	4/32	0.58	0.52	0.81	0.105	16.0
10	Caustic quebracho driscose, Oklahoma — 1,300 ft	9.7	11.0	57.2	8	20	5.6	2/32	1.12	0.93	0.78	0.19	23.5
11	Caustic quebracho driscose, Oklahoma — 2,375 ft	9.9	11.3	21.5	0	3	6.2	2/32	1.11	0.92	0.89	0.09	23.0
12	Caustic quebracho driscose, Oklahoma — 4,295 ft	9.7	10.2	9.4	0	1	6.9	2/32	1.31	1.15	0.74	0.21	21.0
13	Caustic quebracho driscose, Oklahoma — 5,600 ft	10.2	10.4	43.5	3	10	4.5	1/32	1.41	1.25	0.82	0.105	27.0
14	Caustic quebracho driscose, Oklahoma — 5,812 ft	10.2	9.2	25.1	0	3	5.2	2/32	1.28	1.12	0.90	0.09	24.0
15	Natural, Venezuela	10.1	9.0	42.7	0	1	9.0	3/32	2.3	2.1	0.84	0.20	44.0
16	Natural, Venezuela	10.2	9.2	45.0	0	2	8.0	2/32	8.0	7.0	0.83	0.28	60.0
17	Chemical, Mississippi	10.1	8.0	69.3	..	..	14.0	3/32	3.7	2.74	0.71	0.36	30.5
18	Lime-caustic-quebracho-impermex, Mississippi	10.85	12.6	15.8	0	5	8.6	1/32	1.55	1.31	0.80	0.24	33.0
19	Lime-caustic-quebracho-impermex, Mississippi	10.95	12.5	17.5	0	0	9.0	1/32	1.4	1.18	0.80	0.21	30.0
20	Water-base gel, Mississippi	9.5	7.8	..	..	..	17.6	3/32	2.7	2.23	0.71*	0.33	22.5
21	Chemical, starch base, Mississippi	11.1	9.4	37.1	0	34	12.5	4/32	1.3	1.07	0.90	0.16	38.5
22	Silicate, Texas	14.9	10.0	>120	5	75	30.4	8/32	0.33	0.28	0.59	0.029	1.15
23	Salty, Denmark	10.0	7.7	13.1	0	1	34.2	4/32	0.06	0.058	..	..	Negligible

*to 200 psi

Tests

All muds were first tested at room temperature, the potential difference between the two calomel electrodes being recorded for increasing gauge pressures over a range from 0 - 500 psi. In nearly all cases, readings were also taken with decreasing pressures. In most experiments, little difficulty was found in returning to the original calomel electrode potential difference on releasing the pressure to atmospheric, but it may be said that unless the original potential is attained within the reproducibility of the potassium chloride junction potentials, the results of the run must be disregarded. In certain instances, alterations of as much as 20 mv were observed in the electrode zero, this potential being destroyed by washing the end of the internal calomel electrode with distilled water. It was apparent that this phenomenon only occurs when a particle of clay lodges firmly across the tiny entrance to the potassium chloride leak in the electrode tip. The clay particle then separates a saturated potassium chloride solution from mud filtrate with the consequence that an electrochemical cell is set-up which, although inefficient, is still capable of setting up a very appreciable emf when separating solutions of widely differing activities.

In high temperature experiments, it must be noted that in addition to the mud, both the internal and external calomel electrodes must also attain temperature equilibrium. If this is not achieved, a drift of the electrode zero will occur owing to changes occurring in the *KCL* concentrations within the electrodes.

Plots of total filtrate versus pressure for given times of filtration were obtained by using substantially the same apparatus as in Fig. 1. The capillary tube with filtrate reservoir was, however, replaced with a short narrow capillary tube bent downward so as to deliver into a 5 cc. graduate vessel.

In experiments involving the building-up of the filter cake on a sandstone basis the filter disc was removed from the cylinder and replaced with 5 mm thick discs of a consolidated Pennsylvania sandstone having a permeability of *c* 300 md and porosity of *c* 0.20. These sandstone discs proved to be force fits in the Lucite cylinder when cut with a 1-in. diamond drill and no circumferential sealing proved to be necessary.

The range of pressure differentials which it was found convenient to cover extended from 0 to 500 psi. This pressure range is equivalent to hole depths down to 7,500 ft in rotary-drilled wells assuming normal bottom-hole pressures and mud weights up to about 75 lb per cu ft. In modern deep drilling, particularly if heavy muds are carried and bottom-hole pressures are abnormally low, differential pressures exceeding 2,000 psi occur. However, it was felt that 500 psi covered directly a reasonably extensive range of drilling conditions and that any conclusions based on observations over this pressure range would in all probability be applicable also under conditions of higher pressure differentials. The results obtained have not led to any serious modification of this supposition.

RESULTS

Preliminary experiments were designed to investigate the streaming potential effects occurring when mud filtrate flowed through the low-pressure side of the apparatus at velocities appropriate to actual filtration conditions. With this object filtrates were obtained from muds numbered 2, 6 and 17 in Tables I and II: these filtrates thus cover a wide range of resistivities. The apparatus was assembled with a Whatman No. 42 filter paper in place and with filtrate half filling the cylinder and entirely filling the channels in the lower Lucite plug and capillary leading to the external filtrate reservoir. The filtrate was then permitted to flow under gravity head and the potential between the calomel electrodes determined both in the absence of flow and while flow occurred. Although the rates of flow under these conditions were found to be far greater than that obtaining during any filtration experiment, no measurable streaming potentials could be detected.

An investigation was then made of the effect of employing the convenient filter disc and filter paper as filter bed as opposed to the more realistic consolidated sandstone. Experi-

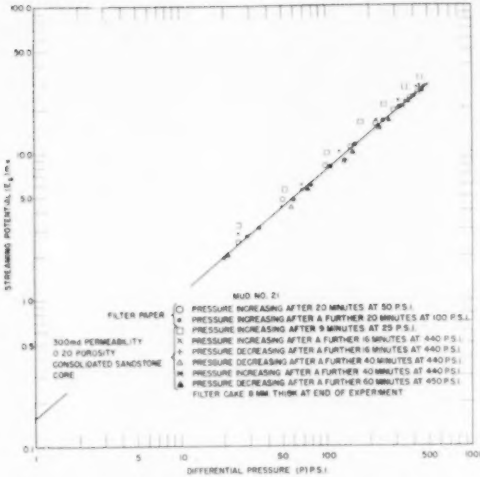
STREAMING POTENTIAL (Es) m.v.
DIFFERENTIAL PRESSURE (P) P.S.I.
MUD NO. 21
FILTER PAPER
PRESSURE INCREASING AFTER 20 MINUTES AT 50 P.S.I.
PRESSURE INCREASING AFTER A FURTHER 20 MINUTES AT 100 P.S.I.
PRESSURE INCREASING AFTER 9 MINUTES AT 25 P.S.I.
PRESSURE INCREASING AFTER A FURTHER 15 MINUTES AT 440 P.S.I.
PRESSURE DECREASING AFTER A FURTHER 15 MINUTES AT 440 P.S.I.
PRESSURE DECREASING AFTER A FURTHER 40 MINUTES AT 440 P.S.I.
PRESSURE INCREASING AFTER A FURTHER 40 MINUTES AT 440 P.S.I.
PRESSURE DECREASING AFTER A FURTHER 60 MINUTES AT 450 P.S.I.
FILTER CAKE 8 MM THICK AT END OF EXPERIMENT
300md PERMEABILITY
0.20 POROSITY
CONSOLIDATED SANDSTONE CORE

FIG. 2 — EFFECT OF FILTRATION TIME AND NATURE OF FILTER BED MATERIAL ON STREAMING POTENTIAL/DIFFERENTIAL PRESSURE RELATIONSHIP.

ments have been reported[11] which show that the effect of the filter bed material on the rate of filtration of a number of drilling muds while small, is not entirely negligible.

Fig. 2 shows the results obtained when mud No. 21 was filtered first with the filter disc and Whatman's No. 42 filter paper and then with a 5 mm thickness of consolidated Pennsylvanian sandstone as the filter bed. The results have been plotted in detail on a log-log scale since this type of plot has invariably been found to give remarkably good straight line correlations between pressure differentials inducing flow and the streaming potentials set up. Fig. 2 graphically illustrates a number of points which have been found to be characteristic of most of the muds investigated. The initial plot of streaming potential against pressure differential obtained when sufficient filtrate has been evolved to complete the electrical circuit between the internal and external calomel electrodes is generally a good straight line on a log-log plot but is displaced relative to the points obtained at later stages in the filtration process. While not marked in Fig. 2, these first points may also yield a line having an appreciably different slope from those obtained in later plots. As the filtration process is prolonged and the filter cake thickens, the reproducibility of the plot improves and a stage is rapidly reached when continued filtration makes no appreciable difference to the plot obtained. Fig. 2 is also characteristic of those muds which appear to be entirely reversible, i.e., essentially the same plot is obtained whether the recording is done with increasing or decreasing pressure differentials. Certain muds, however, as will be shown below, are less satisfactory in this respect. In all the muds tested the zeta potential was found to be negative, i.e., the filtrate was positive with respect to the mud.

Fig. 2 shows that after a small thickness of filter cake has been built-up, there is little significant difference between the results obtained on a filter bed of filter paper and one of sandstone. This was confirmed by additional experiments and in consequence the data recorded in this paper are for filter cakes built-up on the filter disc and Whatman's No. 42 filter paper as a filter bed. It may be noted that in Fig. 2 the thickness of the filter cake on the sandstone at the end of the experiment was found to be 8 mm. The fact that beyond a small limiting thickness of filter cake the streaming potential proved to be independent of cake thickness is of interest both theoretically and from a practical standpoint. In this work, experiments on any one mud were continued until reproducible plots were obtained which were independent of continued filtration. The slopes of the best lines drawn through the points plotted for increasing pressure differentials were measured as well as the intercept defining the streaming potential at 1 psi differential pressure (0.16 mv in Fig. 2). These data are recorded in Tables I and II.

Fig. 3 shows an example where the plot of streaming potential versus pressure differential is markedly different when the pressure is decreased from that obtaining when the pressure is increased. This phenomenon is almost certainly a function of the recovery time of a compressible filter cake when the pressure is released. This may be qualitatively shown by prolonging the period of waiting at any pressure as the pressure is diminished before a potential measurement is made. A slow change of potential in the direction of coincidence with the value obtained on an increasing pressure plot is noted. It was not, however, considered generally necessary to await the attainment of equilibrium in this manner since satisfactory plots could be readily obtained by increasing the pressures. It may be noted that Fig. 3 is evidence that at zero pressure the filter cake returns fairly rapidly to a condition characteristic of this pressure since increasing the differential pressures in the final run reproduced the original slope and position of the linear plot. After the necessary pressure reduction from 480 psi to zero had been made, there was a pause of only two minutes before the pressure was incrementally increased to make this run.

With one exception, all the muds tested attained equilibrium at a particular differential pressure at room temperature as the differential pressures were increased within a time less than that necessary to balance the potentiometer and make a reading. The exception was the laboratory prepared fresh water clay mud (No. 2). When testing this mud, a slow drift

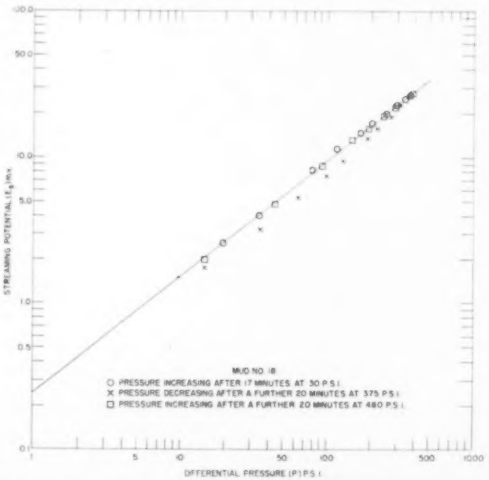
STREAMING POTENTIAL (Es) m.v.
DIFFERENTIAL PRESSURE (P) P.S.I.
MUD NO. 18
PRESSURE INCREASING AFTER 17 MINUTES AT 30 P.S.I.
PRESSURE DECREASING AFTER A FURTHER 20 MINUTES AT 375 P.S.I.
PRESSURE INCREASING AFTER A FURTHER 20 MINUTES AT 480 P.S.I.

FIG. 3 — EXAMPLE OF A MUD SHOWING SLOW EQUILIBRIUM ATTAINMENT AS DIFFERENTIAL FILTRATION PRESSURE DECREASES.

occurring over a period of about 30 seconds was noted before an equilibrium steady potential could be measured. The particular reasons for the exceptional behavior of this mud are not clear.

Several muds gave at room temperature, a linear plot on log-log scales up to a certain pressure differential and beyond this pressure differential the slope of the line changed rather abruptly. Examples of this effect, which was quite reproducible, are shown in Figs. 4 and 5. Plotted also on these figures are the squares of the total filter loss in ccs occurring in constant time at various constant applied pressure differentials. For comparison, Fig. 6 gives the same type plots for a mud which showed a linear log-log relationship between streaming potential and pressure differential. It will be observed that breaks in the straight-line log-log plots of streaming potential are also accompanied by breaks in the filtrate loss plots, although the pressures at which the breaks occur in Fig. 4 do not appear to be identical. In this example, separate runs of the filter loss occurring in two different times were made. Fig. 4 is particularly interesting, inasmuch as the filtrate loss in a given time does not increase with increasing pressure of filtration, whereas the streaming potential shows a marked increase as the pressure increases over the same range. Further experiments have confirmed the fact that a break in the slope of the log-log plot of streaming potential versus pressure differential also involves a break in the log-log plot of filtrate volume per unit time against constant filtration pressure.

Fig. 7 is a composite plot of the best correlations found between streaming potential and pressure differential at room temperature for all the muds tested and serves to show the very considerable influence of the nature of the mud on the magnitudes of the streaming potentials induced by the same range of pressure differentials.

Fig. 8 is a plot of the intercept of the extrapolated straight lines with the ordinate at 1 psi, against mud resistivity. Although the scatter of points is fairly considerable, it will be observed that there is a clear correlation between the value of this intercept and the resistivity of the mud at the

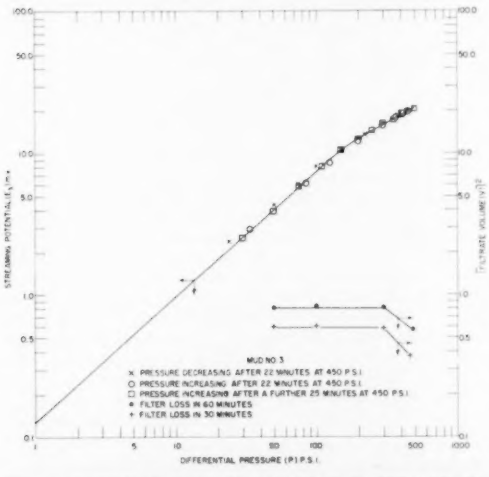
MUD NO. 3
× PRESSURE DECREASING AFTER 22 MINUTES AT 450 P.S.I.
○ PRESSURE INCREASING AFTER 22 MINUTES AT 450 P.S.I.
□ PRESSURE INCREASING AFTER A FURTHER 25 MINUTES AT 450 P.S.I.
• FILTER LOSS IN 60 MINUTES
+ FILTER LOSS IN 30 MINUTES
DIFFERENTIAL PRESSURE (P) P.S.I.

FIG. 4 — EXAMPLES OF MUD SHOWING BREAKS IN STREAMING POTENTIAL/DIFFERENTIAL PRESSURE AND (FILTRATE VOLUME)^2/DIFFERENTIAL PRESSURE LINEAR PLOTS.

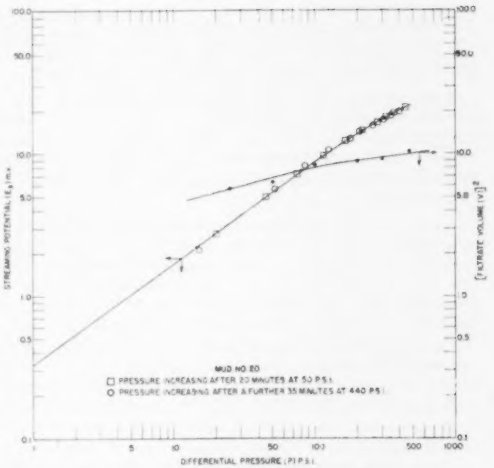
MUD NO. 80
□ PRESSURE INCREASING AFTER 20 MINUTES AT 50 P.S.I.
○ PRESSURE INCREASING AFTER A FURTHER 35 MINUTES AT 440 P.S.I.
DIFFERENTIAL PRESSURE (P) P.S.I.

FIG. 5 — EXAMPLE OF MUD SHOWING BREAKS IN STREAMING POTENTIAL/DIFFERENTIAL PRESSURE AND (FILTRATE VOLUME)^2/DIFFERENTIAL PRESSURE LINEAR PLOTS.

temperature of testing. This temperature was approximately 77°F in all cases.

Streaming potential measurements at temperatures above atmospheric were made on six of the available muds. The results obtained are shown in Figs. 9, 10, 11, 12 and 13. The securing of data at elevated temperatures proved to be somewhat more difficult and tedious than had been the case in the room temperature work. In almost all tests, the attainment of an equilibrium streaming potential at a particular pressure differential was found to be markedly slower than at room temperature. This slowness seemed to become more evident as the temperature of measurement increased and in this respect the behavior of all muds resembled the previously noted behavior at room temperature of mud No. 4. In spite of this difficulty, reproducibility was satisfactory and the variation in the slopes of the linear plots and particularly the breaks in these slopes (noted in Fig. 10) are believed to be genuine.

FIELD TEST

A field test suitable for establishing that the total SP opposite any formation is satisfactorily accounted for by the algebraic sum of electrochemical and electrokinetic potential effects must be performed under rather carefully controlled conditions if it is to be deemed reliable. In particular, it is necessary to measure with care the salinity of the connate water in the formation of interest, to determine accurately both the formation bottom-hole pressure and the actual hydrostatic head of mud in the hole, and to ensure that the formation thickness, resistivity, freedom from shale interbedding and lack of filtrate invasion all fulfill the requirements[5] for maximum SP development.

These conditions were satisfactorily achieved in a Mid-Continent well where the probable existence of two thick and clean water sands had been established from observations in adjacent wells. In the test well these two sands were diamond cored and the cores examined for presence of shale interbedding or interstitial clays. Although some minor shale

streaks were present, both cores were substantially clean, somewhat friable sands, with formation factors of about 12 over thicknesses of 50 ft or more in each case. The SP kicks opposite these sands were also of the flat-topped kind.[3]

At the cessation of diamond coring in each sand, a packer was run on tubing in the rathole and the formation water produced by swabbing the well until the fluid produced gave constant readings of density and resistivity. It is believed that excellent samples of the formation waters were obtained by this technique.

The bottom-hole pressures and temperatures and the hydrostatic head of mud opposite the center of each tested formation were also determined, and a sample of the mud in the hole was in each case secured just prior to the running of the electric logs. The muds secured were Nos. 10 and 11 in Table II. The essential data are given in Table III.

Fig. 14 shows a convenient method of plotting *NaCl* activity, resistivity and salinity data on the same curve so as to facilitate computation of the required activities from the usual salinity and resistivity data. The necessary mean activity coefficients were taken from Latimer,[17] while the resistivity-salinity data are from the International Critical Tables, interpolations being made where necessary. To plot this curve, the mean activity for any concentration of *NaCl* is determined from Latimer's activity coefficient data. These activities are plotted against the resistivity of the corresponding sodium chloride solution at a temperature of 64°F, to give the dashed line shown. Since activity is substantially independent of temperature,[5] it follows that by moving across the chart from the dashed line parallel to the abscissa, the concentration of *NaCl* corresponding to the *NaCl* activity indicated on the upper scale is obtained when the solid 64°F line is intersected. The resistivity of a solution of this activity at any other temperature is then found in the usual manner by moving downwards parallel to the resistiviy axis to intersect the line of appropriate temperature. To find activity from a resistivity measurement (assuming the solution to be *NaCl*) this procedure is reversed. Thus, from the data in Table III, the activity of a 32,232 mg./L. solution is approximately 0.36. While that of a 156,350 mg./L. solution is approximately 1.65.

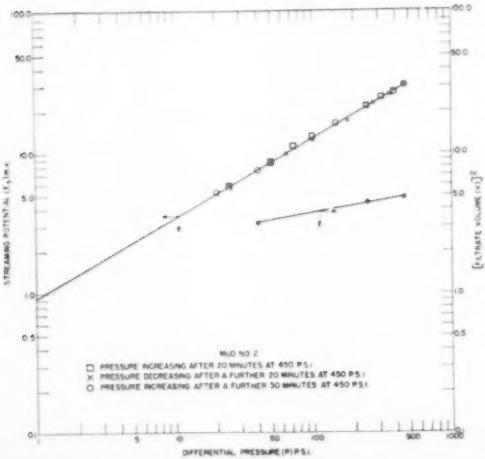
MUD NO. 2
PRESSURE INCREASING AFTER 20 MINUTES AT 450 P.S.I.
PRESSURE DECREASING AFTER A FURTHER 20 MINUTES AT 450 P.S.I.
PRESSURE INCREASING AFTER A FURTHER 30 MINUTES AT 450 P.S.I.
DIFFERENTIAL PRESSURE (P) P.S.I.

FIG. 6 — EXAMPLE OF LINEAR STREAMING POTENTIAL/DIFFERENTIAL PRESSURE AND (FILTRATE VOLUME)²/DIFFERENTIAL PRESSURE PLOTS.

Similarly, a mud resistivity of 1.12 at 64°F corresponds to a salinity of 5,800 mg./L. and an activity of approximately 0.08. A resistivity of 1.11 at 64°F gives the same value within the accuracy of the chart. Thus, for the 1,300 ft sand,

$$\frac{\text{Activity of connate water}}{\text{Activity of mud}} = \frac{0.36}{0.08} = 4.5$$

From Fig. 15 which is a more accurate* version of Fig. 1,

Table III

	1300-ft Sand	2375-ft Sand
Water Analysis (mg./L.)		
Na	11,691	48,982
Ca	446	8,310
Mg	210	2,254
SO₄	1,140	nil
Cl	18,364	96,780
HCO₃	381	24
	32,232	156,350
Bottom-hole pressure	452 psi	963 psi
Mud pressure	660 psi	1247 psi
Differential pressure	208 psi	284 psi
Formation temperature	87°F	98°F
SP	53.5-55.0 mv*	109-111 mv*

*Data from the several SP logs run

Reference 1, this corresponds, at 87°F, to an electrochemical SP of approximately 47 mv. Thus, the discrepancy between the measured SP and the calculated SP is between 6.5 and 8.0 mv. Fig. 13 gives the laboratory streaming potential curve at 90°F for a sample of the mud in the hole at the time the electric log was run. For a pressure differential of 208 psi, the streaming potential is about 11 mv, and the sign of this potential is such that it would increase the numerical (negative) value of the total SP.

For the 2,375 ft sand, the activity ratio is, similarly, $1.65/0.08 = 20.7$. At 98°F, this corresponds to an electrochemical emf of about 96 mv. Hence, the discrepancy between the electrochemical and the total SP measured is here from 13 to 15 mv. From Fig. 13, for a pressure differential of 284 psi the laboratory determined streaming potential at 97°F is about 14 mv. For both sands the difference between the computed and measured streaming potentials is well within the experimental errors involved.

It is of interest in the case of the 2,375 ft sand to note the errors involved if, assuming no knowledge of streaming potentials, calculations of salinity are made on the basis of an SP kick of 110 mv. The activity ratio of 98°F is then 32 and hence the connate water activity is (32) (0.08) or 2.56. From Fig. 14 the salinity is thus about 210,000 mg./L. or 0.06 ohm-meters at 64°F. If the ratio is assumed to be a resistivity ratio, the connate water resistivity would be given by 1.11/32 or 0.035 ohm-meters at 64°F. This represents a highly supersaturated sodium chloride solution, although the error between this resistivity and the true resistivity corresponding to 156,350 mg./L. — 0.066 ohm-meters at 64°F — could be tolerated in approximate log interpretations. Alternatively, of course, by arbitrarily assuming a higher value for the electrochemical constant $2\bar{t}RT/F$ the correct answer could be obtained. There is, however, no theoretical rationale for such a procedure.

One further test made in the above-mentioned Mid-Continent

*This curve has been recalculated from the equation $E = 2\bar{t}\, RT/F \ln a_c/a_m$. The symbols were defined in the Introduction. Since $\bar{t}$ is not a true constant but is a function of temperature and concentration this should be taken into account in plotting Fig. 15. The temperature effect is easily incorporated, but for general applicability some mean value of concentration must be chosen. For this purpose, the values for *2N NaCl* were selected. Fortunately, the variation of $\bar{t}$ with concentration is not large.

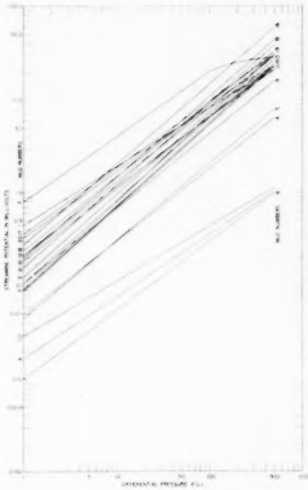

FIG. 7 — RELATIONSHIP BETWEEN STREAMING POTENTIAL AND DIFFERENTIAL PRESSURE FOR ALL MUDS TESTED. MUD NOS. REFER TO TABLES I AND II.

well deserves record, although for a number of practical reasons high experimental precision could not be achieved. At a depth of 4,100 ft in this well, the hydrostatic pressure on the borehole mud column was increased by the expedient of fitting a Schlumberger stuffing box to the well head, speeding up the mud pumps and controlling the pressure developed by judicious bleeding of the mud line. Pressures so developed were read-off on the ordinary mud-pressure gauge and at the same time a SP log was run. The increased mud pressure could not be kept constant but during the running of the SP log appeared to fluctuate only between 200 and 240 psi. Assuming a mean increase of pressure of about 220 psi, it is interesting to compare the increase in SP which would be expected to result from this pressure increase with the increase in SP actually occurring. Such a comparison can only be made on the basis of the very approximate assumption that the mud filter cakes plastering-off the formations are very similar in streaming potential characteristics to those plotted in Fig. 13. Table IV gives the increased SP values for a number of formations in the depth range 765 ft to 3,670 ft.

It will be observed that the increase in SP resulting from the measured mud pressure is not constant nor is there any marked depth trend. The increases noted are at least similar to those which would result from increasing the pressure of Mud No. 10 from 208 to 428 psi and Mud No. 11 from 284 to 504 psi.

DISCUSSION OF RESULTS

In a discussion of the results obtained in this work, it appears desirable first to summarize those conclusions which stem directly from the observations made. A second step is to examine the results and conclusions in the light of such basic theoretical considerations as appear to be applicable, and thus to assess not only the rationality of conclusions which are necessarily based on relatively few experimental data but also to confirm, if possible, their range of applicability. A third step is to examine the practical utility of the conclusions reached.

Firstly, the data in Tables I and II show that neither the normal 30-minute water loss of the standard cake test nor the conventional gel strength or viscosity tests offer any guide to the streaming potential characteristics of a drilling mud. Of all the commonly made mud tests only the mud resistivity at room temperature (*c* 77°F) offers any reliable indication of streaming potential characteristics. The data supporting this contention have been plotted in Figs. 7 and 8.

It would appear that the following relationship between the streaming potential and the pressure differential inducing flow across a filter cake is applicable to drilling muds.

$$E_s = kP^y \quad \ldots\ldots\ldots\ldots \quad (1)$$

Where, E_s = streaming potential, P = pressure differential and k = constant, y = constant.

Fig. 8 indicates that k is considerably dependent upon mud resistivity, thus exerting a major influence on the total value of E_s for any value of P. However, Fig. 8 shows also that no accurate estimate of k is possible purely from a knowledge of mud resistivity, while Fig. 7 shows graphically the controlling effect of the magnitude of the exponent y and also the fact that

Table IV
Increase in SP resulting from *c* 200 psi increase in borehole mud pressure

Depth (ft)	Increase in SP (mv)	Approx. Increase (From Fig. 13)	Depth (ft)	Increase in SP (mv)	Approx. Increase (From Fig. 13)
765	10.0		2245	8.6	
967	8.4		2330	7.4	
1142	5.7		2420	8.8	9.5
1235	7.0		2503	9.4	
1272	5.6		2642	5.7	
1335	7.4	9.0	2700	0.7	
1525	7.0		3068	8.9	
1640	5.7		3422	5.1	
1816	6.4		3435	0.5	
1850	7.1		3582	6.3	

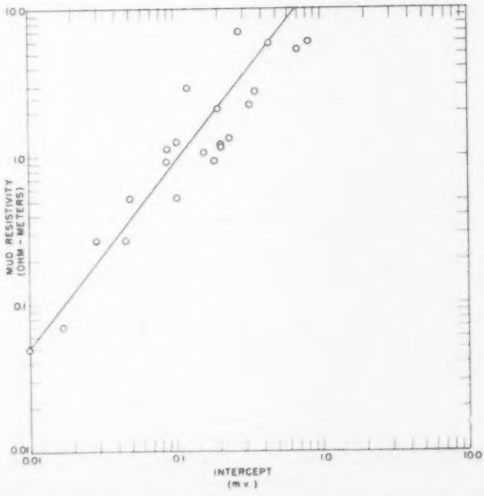

FIG. 8 — RELATIONSHIP BETWEEN MUD RESISTIVITY AT 77°F AND CONSTANT k IN RELATIONSHIP, $E_s = kP^y$.

y need not necessarily be a constant for all values of P. No conventional mud test data appear to give any indication of the value of the exponent y. However, it has been indicated above that a change in the value of y appears to be accompanied by a corresponding alteration in the slope of the log-log plot of the square of the quantity of filtrate produced in a given time versus the differential pressure of filtration. Nevertheless, the slope of this line, as may be seen from Figs. 4, 5 and 6, is not equal to y.

The experimental determination of streaming potential as a function of pressure differential for a particular mud at different mud temperatures indicates that the streaming potential at any given pressure differential is affected by temperature. Although the changes induced by temperature are relatively small in the case of the muds tested in this work, in all cases changes in both k and y were observed. The direction of these changes, i.e., whether an increase or decrease in magnitude, does not appear to be subject to forecast and, in addition, Fig. 10 shows that a mud in which the pressure exponent is constant up to a particular pressure differential at room temperature may not retain this constancy up to the same pressure differential when the mud temperature is increased. Thus, the streaming potential/pressure differential relationship of a mud obtained at one temperature cannot be used to forecast accurately the relationship between these variables at some other temperature. This inability to forecast mud properties at one temperature on the basis of observations made at some other temperature was also the experience of Byck[18] when investigating mud filtrate losses as a function of mud temperature.

Four basic experimental observations need theoretical substantiation and explanation before their universal applicability can be fully assessed. These are: (a) the dependence of k on mud resistivity, (b) the independence of filter cake thickness on streaming potential once a minimum cake thickness has been built up, (c) the relationship between filter loss and the exponent y, (d) the relatively small but unpredictable variation of streaming potential characteristics with mud temperature.

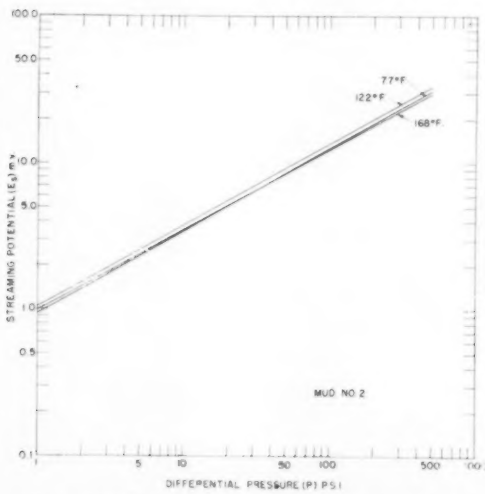

FIG. 9 — INFLUENCE OF TEMPERATURE ON STREAMING POTENTIAL/DIFFERENTIAL PRESSURE RELATIONSHIP, MUD. NO. 2.

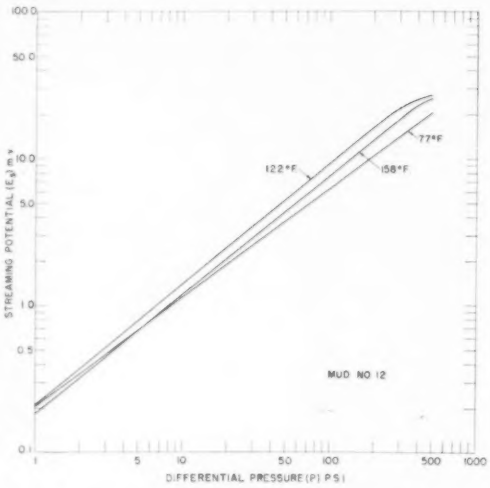

FIG. 10 — INFLUENCE OF TEMPERATURE ON STREAMING POTENTIAL/DIFFERENTIAL PRESSURE RELATIONSHIP, MUD NO. 12.

From D'Arcy's Law the following equation may be derived for flow through a non-compressible filter cake supported on a filter bed:

$$dV/d\theta = \frac{PA}{Z(rL + R)}$$

Where,

$dV/d\theta$ = rate of flow of filtrate in unit volume/unit time
P = pressure differential causing flow
A = area of filter cake and filter bed
Z = viscosity of filtrate
r = specific resistance to flow of filter cake
L = thickness of filter cake
R = initial resistance of unit area of filter bed

But, $L = vV/A$

Where, v = volume of filter cake deposited by unit volume of filtrate

Thus, $$dV/d\theta = \frac{PA^2}{Z(rvV + RA)} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

For compressible filter cakes the specific resistance to flow, r, is not independent of the differential pressure causing filtration but is itself a function of the applied differential pressure. For convenience and following the suggestion of Lewis and his co-workers[19] this may be written in the form, $r = r'P^s$, where r' and s are constants characteristic of a particular filter cake. It is, however, well to note that as pointed out by Carman[20] the Lewis equation implies that the resistance, r, is zero at the face of the cake where the pressure differential P is zero. This in turn implies that there is no sharp boundary between the filter cake and mud during filtration. This is readily observed to be quite untrue and a clear line of demarcation between cake and mud was always noted in this work. However, equations of the form, $r = r''(1 + k''P)^s$, where k'' is also a constant, which express this latter fact, are of the same form as the Lewis relationship and do not materially affect conclusions based on the simpler Lewis expression. Hence, $r = r'P^s$ will be here used. Similarly, R is not independent of pressure but may be written $R = R'P^m$, where m is a positive fraction. Hence, for compressible filter cakes,

$$dV/d\theta = \frac{PA^2}{Z(r'P^s vV + R'P^m A)} \quad \ldots\ldots (3)$$

In the case of drilling muds where the entire accent has been put on a high value of the specific resistance, r, the passage of a relatively small quantity of filtrate V serves to make $r'P^s vV \gg R'P^m A$.

Thus, when a relatively small thickness of mud filter cake has been built up, Equation (3) may be simplified to,

$$dV/d\theta = \frac{PA^2}{Zr'P^s vV} = \frac{P^{1-s}A^2}{Zr'vV} \quad \ldots\ldots (4)$$

Integration of Equation (4) at constant pressure gives:

$$\frac{Zr'v}{A^2} \cdot \frac{V^2}{\theta} = 2P^{1-s} \quad \ldots\ldots (5)$$

Hence, if the time, θ, is held constant, since $Zr'v$ and A^2 are constant for any particular mud and filtration system at constant temperature it follows that:

$$\text{Constant} \cdot V^2 = P^{1-s} \quad \ldots\ldots (6)$$

or that the slope of the plot of V^2 versus P on a log-log scale will be $(1-s)$. This is the reason for the plotting of V^2 versus P in Figs. 4, 5 and 6. A break in the normal straight line plot indicates that flow resistance is not increasing as a constant power function of the applied pressure differential.

The foregoing is a simplified picture of a complex and not fully understood process. It may be noted that the resistance to flow is not a constant across a filter cake subjected to a given pressure differential, but varies with variations in porosity across the filter cake (the porosity being least at the low-pressure face, highest at the high-pressure face). This problem has been considered at length by Carman in his excellent critical review of fundamental filtration processes[20] and it is unnecessary here to repeat his proof that, in spite of the non-homogeneous nature of compressible filter cakes, their resistance is solely a function of the total pressure differential across them.

The theoretical computation of the streaming potential across compressible filter cakes is not a matter which appears to have received any prior treatment in the literature. One important aspect of the problem as it pertains to mud filter cakes has, however, been noted by Bikerman[21] who pointed out that if the matrix of a granular bed were itself a conductor any streaming potential equation must be modified to incorporate this fact. Thus, in a non-compressible granular bed in the region of laminar flow, the velocity of flow is directly proportional to the pressure differential inducing flow (Darcy's Law). If the normal assumption is made that the magnitude of charge flowing is directly proportional to the rate of fluid flow, it follows that the rate of electrical charge flow (current) is also directly proportional to the pressure differential. The streaming potential is the product of this current and an electrical resistance and the normal streaming potential equation expresses the resistance in terms of a geometrical shape factor and the resistivity of the flowing fluid. This implies that the solid matrix is a non-conductor, i.e., that the electrical and hydraulic paths are identical. This is frequently not the case and is never the case in mud filter cakes as presently constituted, since filter cakes contain electrically conducting hydrated clay. Thus, for a mud filter cake the effective electrical resistance is clearly the total filter cake resistance.

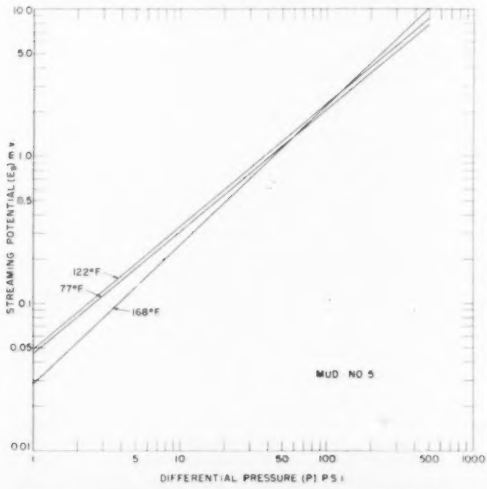

FIG. 11 — INFLUENCE OF TEMPERATURE ON STREAMING POTENTIAL/DIFFERENTIAL PRESSURE RELATIONSHIP, MUD. NO. 5.

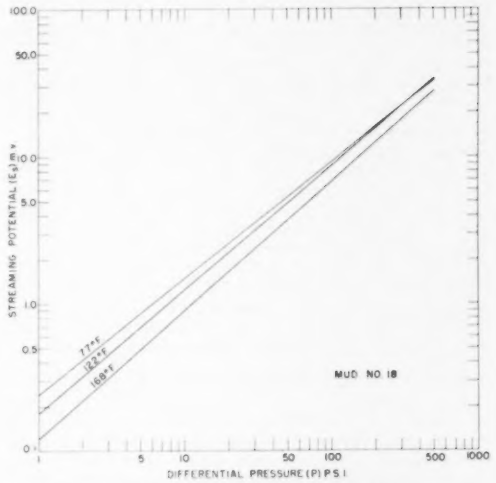

FIG. 12 — INFLUENCE OF TEMPERATURE ON STREAMING POTENTIAL/DIFFERENTIAL PRESSURE RELATIONSHIP, MUD NO. 18.

In deriving an equation for the streaming potential across a compressible filter cake, it is necessary first to compute the actual rate of fluid flow past the solid — or non-flowing-surface. It then follows that the actual magnitude of current flow is the product of this fluid flow rate, the average charge moved per unit area of stationary/flowing interface and the specific surface area of this interface per unit of filter cake volume.

The apparent linear flow rate is $1/A \cdot dV/d\theta = u$, but the actual rate of flow within the pores of the filter cake is greater than this value. Thus, considering a small thickness dL of filter cake having a constant porosity, ϕ, the actual rate of fluid flow u_e is given by:

$$u_e = u/\phi \cdot T^{1/2} \quad \ldots\ldots (7)$$

Where, $T^{1/2} = (\text{tortuosity})^{1/2} = dL_e/dL$

and, dL_e = the actual average length of flow path through the thickness dL.

If S is the specific surface area per unit of filter cake volume of the interface between the moving filtrate and sta-

tionary components of the filter cake, and c is the average charge moved per unit surface area, the current, I, is given by:

$$\begin{aligned} I &= S \cdot c \cdot u_e \cdot A \\ &= S \cdot c \cdot u/\phi \cdot T^{1/2} \cdot A \\ &= S \cdot c \cdot T^{1/2}/\phi \cdot dV/d\theta \\ &= P^{1-s} A^2 S c T^{1/2}/Zr' V \phi \quad \ldots\ldots\ldots \quad (8) \end{aligned}$$

by substituting the value of $dV/d\theta$ from Equation (4).

If ρ_{fc} is the resistivity of the filter cake, the resistance of the cake, R, is given by:

$$R = \rho_{fc} \cdot dL/A \quad \ldots\ldots\ldots\ldots \quad (9)$$

And, $$E_s = IR \quad \ldots\ldots\ldots\ldots \quad (10)$$

Thus, $$E_s = \frac{P^{1-s} A}{Zr' V} \cdot S \cdot c \cdot T^{1/2}/\phi \cdot \rho_{fc} \cdot dL$$

However, $dL = vdV/A$ and thus, dL may be eliminated

Whence, $$E_s = \frac{P^{1-s} \cdot S \cdot c}{Zr'} \cdot T^{1/2}/\phi \cdot \rho_{fc} \quad \ldots\ldots \quad (11)$$

Thus, the streaming potential is independent of cake thickness.

Equation (11) may be written in the form:

$$E_s = \frac{c}{Zr'} S \cdot \frac{T^{1/2}}{\phi} \cdot \rho_{fc} \cdot P^{1-s} \quad \ldots\ldots \quad (12)$$

In Equation (12) for any given mud at a specific temperature (c/Zr') is a constant. From Equation (6) the exponent $(1-s)$ may be obtained by plotting V^2 against P, and it is found that $(1-s) < y$ in the experimentally-determined relationship,

$$E_s = kP^y$$

Thus, it would seem that the group $(S \cdot T^{1/2}/\phi \cdot \rho_{fc})$ is a function of pressure alone such that:

$$S \cdot T^{1/2}/\phi \cdot \rho_{fc} = \text{Constant } P^{y-(1-s)} \quad \ldots \quad (13)$$

The probability of Equation (13) being true may be examined and for this purpose it is desirable to apply to mud filter cakes concepts to account for the permeability phenomena of clays introduced by Kozeny,[22] Zunker[23] and particularly Carman.[24]

Fundamentally, these workers believe that the Kozeny equation for fluid flow through porous media is the basic flow equation for these systems and that any deviations from the Kozeny equation must be subject to rational interpretation in terms of peculiarities in the porous medium giving rise to the anomalies. For clays, they showed that if it is postulated that the true porosity applicable to fluid flow is ϕ' and ϕ' is less than the apparent porosity, ϕ, the Kozeny equation applies to flow through clay beds. In other words, it is postulated that there are immovable water sheaths attached to the clay laminae, and thus, ϕ based on total water content is too large. Data to support this contention have been adduced[24] and it has been shown that in any clay system ϕ' is related to ϕ in the following manner, x being a constant:

$$\phi' = \phi - x(1-\phi) \quad \ldots\ldots\ldots \quad (14)$$

It may be noted that this concept of fixed water sheaths is not at variance with normal theories of the structure of thixotropic mud systems. The concept also explains the fact that clays may have zero permeability but a high water content, i.e., when ϕ' is zero, ϕ is not zero.

A further consequence of the Kozeny-Zunker-Carman theory which results from the peculiar distribution of surface in plate-like clay lamellae, is that, to a close approximation, the specific surface area per unit of bulk volume, S, is related to the specific surface area of the unhydrated (dry) clay, S_o, by the relationship:

$$S = S_o(1-\phi) \quad \ldots \quad (15)$$

and not by the relationship, $S = S_o(1-\phi')$

Equation (13) may then be modified in terms of these concepts to read:

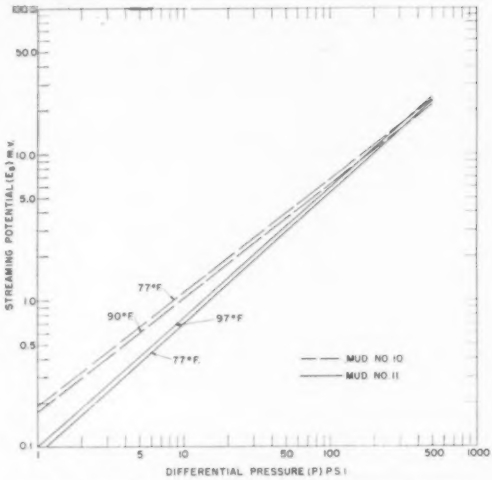

FIG. 13 — INFLUENCE OF TEMPERATURE ON STREAMING POTENTIAL/DIFFERENTIAL PRESSURE RELATIONSHIPS, MUDS NO. 10 AND 11.

$$S_o(1-\phi)\frac{T^{1/2}}{\phi'} \rho_{fc} = \text{Constant } P^{y-(1-s)} \quad \ldots \quad (16)$$

Note that ϕ' replaces ϕ since this porosity term was originally introduced to account for the void volume available to fluid flow.

In Equation (16), S_o is now a constant in a given system and $(1-\phi)$ may be replaced, from Equation (14), by the expression:

$$(1-\phi')/(1-x)$$

Here $(1-x)$ is also a constant for a given mud system.

Thus, Equation (16) may be written as:

$$\begin{aligned} \frac{S_o(1-\phi')}{(1-x)} \cdot \frac{T^{1/2}}{\phi'} \cdot \rho_{fc} &= \text{Constant} \cdot (1-\phi')\frac{T^{1/2}}{\phi'} \rho_{fc} \\ &= \text{Constant } P^{y-(1-s)} \quad \ldots \quad (17) \end{aligned}$$

Equation (17) may be further simplified if $T^{1/2}/\phi'$ is written as F, the formation factor of a system of unconsolidated hydrated clay sheaths. This follows from the derivation of Wyllie and Rose.[25] The work of Fricke[26] shows further that in a particular unconsolidated system of particles the formation factor, F, is essentially a function only of the porosity. Hence, to establish the validity of Equation (17) only the resistivity of the filter cake, ρ_{fc}, remains to be shown to be a function of cake porosity and thus of differential pressure, since there are many experimental data[24] to show the effect of P on ϕ'. The value of ρ_{fc} is partly dependent upon F and hence the resistivity of the flowing fluid network. It is, however, also dependent upon the average resistivity of the hydrated solid particles in the filter cake. This latter resistivity is likely to be relatively independent of pressure-produced porosity changes, but F has already been shown to be a function of effective porosity. Hence, a dependence of ρ_{fc} on the value of P only is probable.

The above equations were derived on the basis of a filter cake of uniform porosity characteristics in order to simplify the relationships. For a real filter cake, the porosity varies with thickness. However, this porosity variation is itself a consequence of the variation in differential pressure across the filter cake. Thus, the expression $(1-\phi')F\rho_{fc}$ is a function of the single variable P at any point in the cake. Hence, the

function must integrate to give a function only of total differential pressure across the filter cake.

In Table V are given some figures to illustrate the difference between the exponents y and $(1-s)$.

It will be seen that this difference varies considerably, the difference being particularly large for the oil-emulsion mud No. 3. This result may be a consequence of the considerable oil content of the filter cake, since this oil must markedly increase the filter-cake resistivity and thus the streaming potential at a given pressure differential. If this is the explanation, it would appear at least theoretically possible to make a mud having an exponent y which exceeds unity.

Table V

Mud No.	Exponent y	Exponent $(1-s)$	Difference
2	0.57	0.18	0.39
21	0.90	0.37	0.53
20	0.71	0.25 (20-200 psi)	0.46
3	0.88	0 (to 140 psi)	0.88
5	0.83	0.35	0.48
6	0.66	0.38	0.28

It has been shown above that the streaming potential across compressible filter cakes, like the streaming potential across non-compressible porous media, should not be dependent upon thickness. In the early stages of filtration the resistance, R, of the filter bed is not negligible, and hence the streaming potential characteristics of this medium may significantly affect the total recorded streaming potential. This seems to be the principal cause for the experimentally observed discrepancy between early streaming potentials for a given pressure differential and later constant values.

Equation (12) shows that the resistivity of the mud filter cake, ρ_{fc}, appears in the expression for streaming potential and it has been noted that this quantity appears to be a function of pressure differential. If ρ_{fc} is written as $\rho_{fc} = \rho_m(n + mP^z)$, where ρ_m is the mud resistivity and n, m and z are constants, the dependence of the constant k in the expression $E_s = kP$ on mud resistivity becomes explicable. The value of the constant n will be affected, particularly, by the quantity of non-conducting solids such as oil or weighting material in the filter cake and by the porosity of the filter cake under zero pressure differential.

The effect of temperature on streaming potential may only be very qualitatively evaluated. It may be noted that resistivity appears in the numerator of Equation (12) and filtrate viscosity in the denominator. Since the variation of aqueous conductivity with temperature is closely similar to the temperature variation of aqueous viscosity, the effect of temperature will be to reduce these two quantities approximately in proportion and a rough cancellation appears probable. The influence of temperature on the magnitude of c is obscure. The relationship

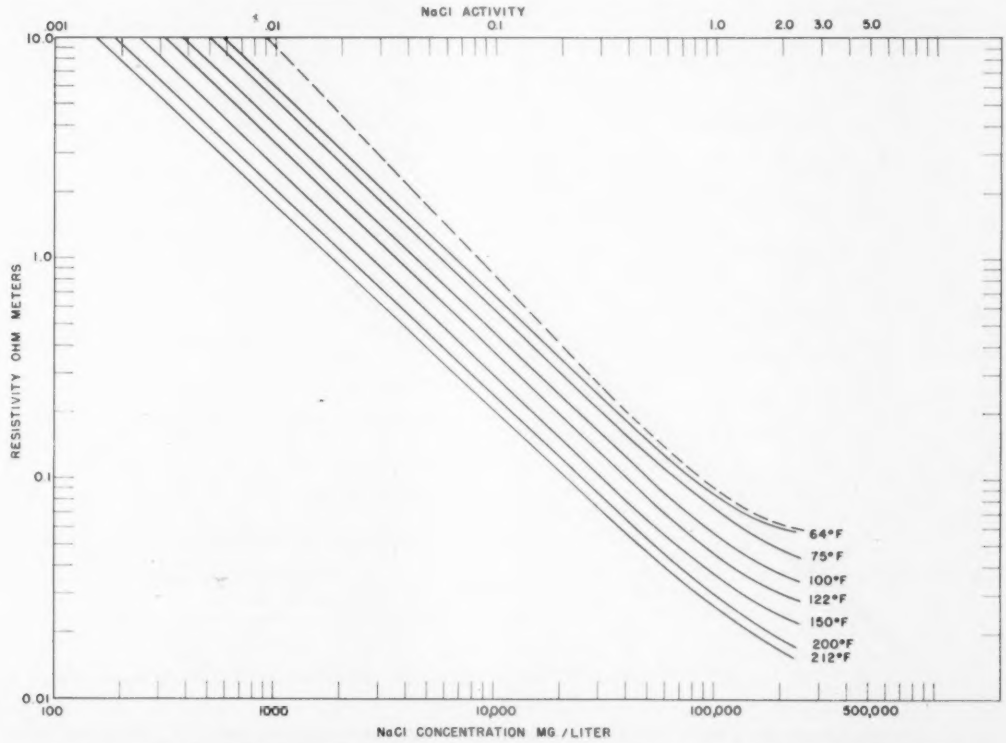

FIG. 14 — CHART FOR INTERCONVERSION OF THE RESISTIVITY, SALINITY AND ACTIVITY OF SODIUM CHLORIDE SOLUTIONS.

between zeta potential and c can only be found if a specific hypothesis as to the distribution of electricity in the double layer at the moving fluid/stationary-surface interface is made. For an idealized plane parallel double layer, if r is the thickness of the double layer, the zeta potential is equal to $4\pi cr/D$, where D is the dielectric constant of the fluid. If an expression of this type applies to the complex filter-cake system and the zeta potential and r remain constant, c will be proportional to D and will decrease about 0.5 per cent °C rise in temperature. However, the zeta potential itself tends to control the stability of a colloidal system and prevent coagulation. The results of Byck[13] on filtrate losses of muds at elevated temperatures tend to show that some flocculation of the filter cake occurs, presumably accompanied by a change in zeta potential as well as r', the specific filter cake resistance. Thus, it would appear that temperature may either increase or decrease the streaming potential for a given pressure differential as a consequence of the complex interplay of a number of imponderables. At any temperature, however, the value of the zeta potential and hence, c, may be expected to be somewhat dependent on the filtrate salinity and thus also on mud resistivity. This dependence probably also contributes to the relationship observed between the streaming potential constant, k, and mud resistivity.

The practical consequences of the streaming potential effect in well logging appear, from the data given, to be of more importance than has generally been believed. It is apparent that when using muds having a resistivity between 1 and 2 ohm-meters at 64°F, streaming potentials of 20 to 30 mv are quite feasible, at depths from 5,000 - 10,000 ft, assuming normal mud weights and bottom-hole pressures. With heavy fresh muds, deep drilling, and particularly, abnormally low bottom-hole pressures, it seems quite possible to have streaming potentials of 50 mv or more constituting perhaps half the total SP and leading to prohibitively serious errors in the calculation of connate water salinities by the electrochemical SP method. These are extreme conditions and it must be recollected that there is evidence from the 0 - 500 psi range of pressure - differential experiments that the exponent y in the relationship $E_s = kP^y$ may not remain constant at the high-pressure differentials envisaged. However, tests have been reported[10] to show that the log-log plot of mud filtrate versus pressure differential may remain a straight line to pressure differentials as high as 3,000 psi; it is thus entirely possible that in many instances the log-log plot of streaming potential versus pressure differential maintains a similar linearity to the highest pressures obtaining even in deep rotary wells.

The experimental determination of the streaming-potential component of the SP curve so as to derive the electrochemical component by difference between the total SP and the electrokinetic SP is not promising. Laboratory experiments on mud samples would represent a prodigous effort on any routine basis, while the method of applying additional borehole mud column pressures and noting the increased SP developed is theoretically feasible but practically profoundly difficult. Thus, theoretically, if $E_s = kP^y$ is assumed, the application of two

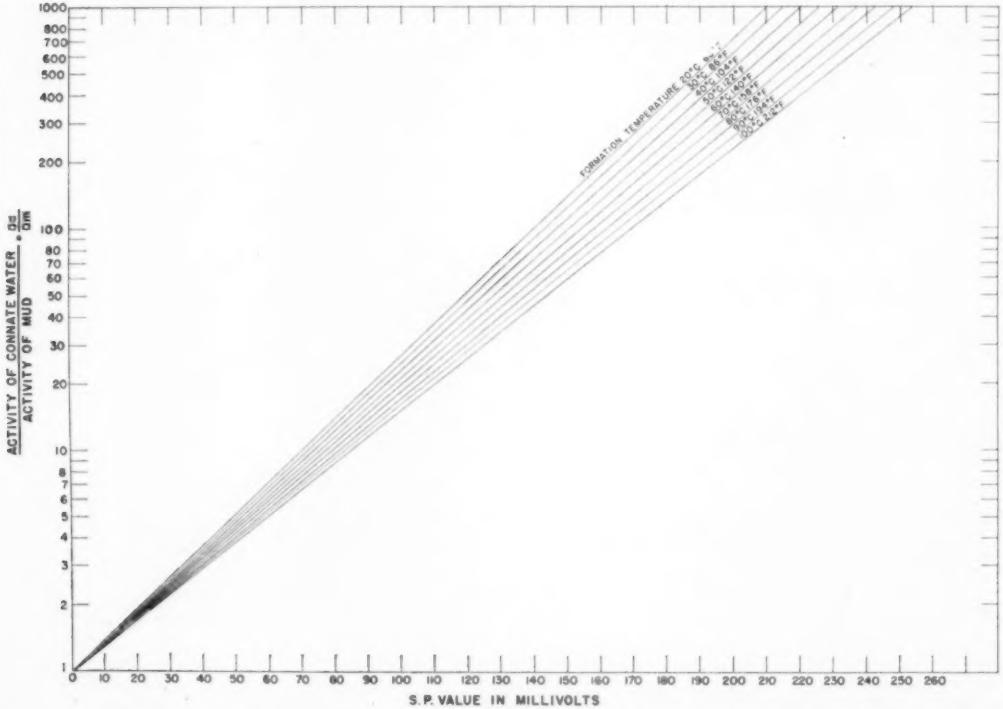

FIG. 15 — RELATIONSHIP BETWEEN CONNATE WATER ACTIVITY RATIO AND CHEMICAL SP FOR VARIOUS FORMATION TEMPERATURES (BASED ON SODIUM CHLORIDE SOLUTIONS).

different hydrostatic pressures (either increased or decreased) to the borehole mud column and the running of three SP curves should enable the constants k and y and thus E_s to be determined if the requisite bottomhole pressure is known. Difficulties result from the small changes in SP induced by the pressure changes imposed on the mud column and the inaccuracies attendant upon picking the necessary shale base lines in each case (see Table IV). The stability of contact potential of the logging electrode becomes a source of serious error when differences of the order of 5 mv are to be measured. More serious even than these technical objections is the necessity of knowing the bottom-hole pressures of the formations of interest. These cannot be reliably assumed and if they are to be measured the formation can in most instances be tested directly, thus destroying the need for any electric-log calculation.

It is probably true that in many wells a small streaming potential component is a blessing in disguise, since the tendency is always for the electrochemical component to be reduced by filtrate invasion, shale interbedding, high formation resistivities and other factors. Thus, the assumption that the measured SP is the electrochemical SP becomes of sufficient accuracy for practical purposes by a compensation of negative and positive (numerical) errors. Nevertheless, although the writer has found this to be true in a very large number of cases, it is clearly undesirable to place undue reliance on an uncontrolled fortuitous compensation of errors of this nature.

The practical solution to the problem of streaming potentials and also to the more accurate calculation of connate water resistivities generally, appears to be the deliberate employment of muds of lower resistivity than has been customary in the past. It has been shown that a lower mud resistivity decreases the streaming potential constant, k, and thus the value of E_s for any value of P. Lower values of y are also desirable but means to achieve this end require further investigation.

The electrochemical emf, $E = 2\bar{\imath}\dfrac{RT}{F} \ln a_w/a_m$

$$= k \ln r$$

where at any temperature and for a particular mud and connate water, k and r are constants.

Thus, $$dE = k\, dr/r$$

$$\therefore \quad \triangle E$$

Therefore, $$\triangle E/E \therefore dr/r \cdot \ln r$$

or, $$\text{error in } r \therefore \triangle r/r = \triangle E/E \cdot \ln r$$

Thus, for any error in the measurement of E, the error in r will be a minimum for small values of r. This conclusion agrees also with the statement of Doll[27] who recommends a small value of r for similar reasons.

Since a decreased mud resistivity implies a higher value of a_m and thus, for any value of a_w, a smaller value of $a_w/a_m = r$ as well as a lower streaming potential, the advantages of low mud resistivities are apparent.

A numerical example based on streaming potentials measured in this work brings out this advantage plainly. Assume a connate water salinity of 100,000 mg./L., formation temperature 86°F and pressure differential of 1,000 psi:

Mud No.	Electrochemical emf (mv)	Streaming Potential mv	Total emf mv	Apparent Salinity from Total emf (mg./L.)
2	−143	−46	−189	Saturated
5	− 45.5	−14.5	− 60	160,000
6	+ 10	− 1.6	+ 8.4	104,000

Additional advantages of more saline muds lie also in the increased accuracy with which estimates of true formation resistivity may be made. A suggestion has been made by Doll[27] that a mud be used which has a resistivity about five times that of the connate water in formations of interest. This suggestion is essentially a compromise and is intended to give not only rather accurate SP logs for the computation of connate water salinities, but sufficient SP development to delineate adequately permeable beds for purposes of correlation.

In addition a mud resistivity similar to that of the connate water resistivity simplifies the interpretation of apparent resistivity logs in terms of true resistivity by keeping to a minimum the adverse effects on such interpretations of the filtrate invaded zone surrounding the borehole. Doll's compromise proposal is reasonable, but the present work indicates the importance of keeping the mud resistivity low in an absolute sense to avoid excessive streaming potentials in wells where mud weights are high and formation pressures low. Thus it may be desirable in wells having low connate water salinities and high pressure differentials to use a mud of lower resistivity and higher activity than the connate water (by a factor again of about 5) and to accept a reversal of the SP curve, i.e., positive SP kicks opposite permeable formations. Such a result is common practice when high activity silicate muds are used at the present time.

ACKNOWLEDGMENTS

The writer is indebted to A. J. Teplitz and F. J. Lydick and their assistants for help in the choice, preparation and routine testing of the laboratory muds used in this investigation. His thanks are due to Paul D. Foote, executive vice-president, Gulf Research and Development Co., for permission to publish this paper.

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APPENDIX

Mud No. 1		
Fibergel 22:	10.89	gms.
Tap water containing 6 per cent Zeogel *pH* adjusted with *NaOH*	350.0	ccs.
Mud No. 2		
Magcogel	17.5	gms.
Baroid "O"	63.0	gms.
Hi-yield clay	6.15	gms.
Tap water	350.0	ccs.
Mud No. 3		
Aquagel	21.0	gms.
Mid-Continent crude	140.0	ccs.
Sodium tallate soap	14.0	gms.
Sodium tripolyphosphate	1.4	gms.
Magcobar	157.5	gms.
Hi-yield clay	14.0	gms.
Tap water	350.0	ccs.
Mud No. 4		
Mud No. 3	350.0	ccs.
Sodium chloride	7.0	gms.
Water	70.0	ccs.
Mud No. 5		
Magcogel	15.75	gms.
Sodium hydroxide	3.4	gms.
Quebracho	3.4	gms.
Lime	3.93	gms.
Hi-yield clay	47.2	gms.
Tap water	350.0	ccs.
Mud No. 6		
Zeogel	8.75	gms.
Magcobar	223.0	gms.
Impermex	8.0	gms.
Tap water + 30 per cent sodium chloride	350.0	ccs.
Mud No. 7		
Aquagel	21.0	gms.
Distilled water	350.0	ccs.
Mud No. 8		
Zeogel	21.0	gms.
Tap water + 30 per cent sodium chloride	350.0	ccs.

DISCUSSION

By H. G. Doll, Schlumberger Well Surveying Corp., Ridgefield, Conn., Member AIME

The question of the streaming potentials occurring with the filtration of drilling mud into permeable beds has been the subject of the attention of various experimenters for years. However as far as I know no systematic and detailed study of the problem had been made theoretically and in the laboratory before Wyllie's work, which is reported in his excellent paper on "An Investigation of the Electrokinetic Component of the Self Potential Curve."

Being given the efforts made toward deriving more and more quantitative data on reservoir characteristics from electrical logs, the publication of the results of this work by Wyllie is quite timely. His paper provides numerous valuable indications which should make possible a more accurate interpretation of the SP logs.

One of the conclusions made by Wyllie is that the electrokinetic component of the SP log should be made as little as possible, and that the use of low resistivity mud should be recommended to this end. This opinion meets the conclusion I arrived at through different considerations.

I would only make the following remark:

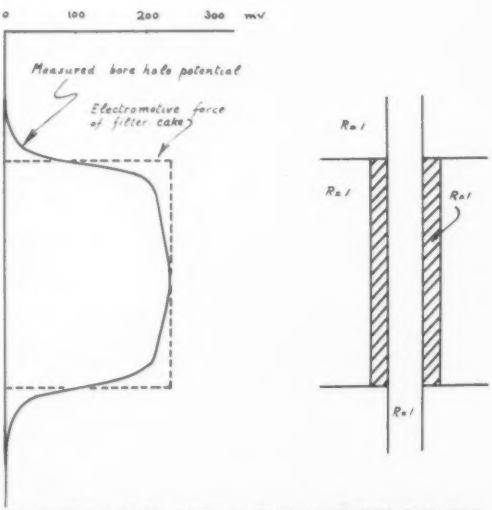
As proposed by the author, when connate water is fresh, the resistivity of the mud can be adjusted below the resistivity of the connate water without being decreased too much, however. The deflections of the SP curve in this case, although reversed, are still large enough to be measured with sufficient accuracy. But, in the case of connate water of high salinity, the use of very low resistivity mud may reduce the spontaneous electromotive forces and, therefore, the amplitude of the deflections on the SP curve, to a very small value. As, on the other hand, these deflections are extremely smooth when mud resistivity is very low, the SP curve may be finally reduced to an almost flat line. I do not think therefore that mud resistivity can be decreased beyond certain limits, without running the risk of ruining the SP log, even for only qualitative purposes.

DISCUSSION

By Hubert Guyod, Consultant, Houston, Tex., Member AIME

In substance Wyllie's paper states that there is an appreciable streaming potential component on the potential graph of electric logs. As evidence, Wyllie points out:

1. That the magnitude of electrochemical potentials is not



SIMULATED STREAMING POTENTIAL, MODEL EXPERIMENT. HOLE DIAMETER, 1; BED THICKNESS, 8.25; FILTER-CAKE THICKNESS, 0.5; ALL RESISTIVITIES, 1; ELECTROMOTIVE FORCE BETWEEN FACES OF FILTER-CAKE, 237 MV.

large enough to explain fully the total potential.

2. That therefore there are substantial streaming potentials.

I do not agree to the foregoing for the following reasons:

1. At the present time we do not know enough about the agencies which produce electrochemical potentials in bore holes to be certain that the fundamental equation

$$V_T = K \log R_e/R_m$$

applies reasonably well to every sand or sandstone.

2. Even if we would be certain that this equation applied, the fact that the observed potential V_o is sometimes greater than V_T should not be construed as meaning that the difference $V_o - V_T$ is due primarily to streaming potentials. As a matter of fact, there are many other possible causes of potential in the ground although it must be admitted that in rotary holes the electrochemical potential is the dominating factor.

3. The fact that, during the field experiments reported by Wyllie, an increase in pressure increased the observed potential does not mean that the potential increase was due to streaming potentials. In fact, an increase in pressure may cause — and probably will cause — an increase in the electromotive force of the electrochemical potentials. While we perhaps know very little regarding this effect it may account for some, if not all, of the phenomenon observed. Another effect of pressure is to increase not only the negative potential opposite sands but also to increase it opposite shales, although to a less degree. This cannot be explained by streaming potentials. Finally, when an extra pressure is applied on the mud column, and then released, the potential does not return immediately to its original value. There is a marked hysteresis effect: it takes from 15 to 60 seconds for the potential to return to its original value. This hysteresis is difficult to explain when streaming potentials are postulated, while it may be less difficult to account for it if it is assumed that another cause of potential is involved, for instance an increase in the electromotive force of the electrochemical potentials.

4. If and when there is a streaming potential component on the potential graph obtained on a thick sand, the top of the potential kick cannot possibly be flat; the reason therefor, is explained in an article which I wrote in the November 27, 1944, issue of *Oil Weekly*. Fig. 15-10 of this article illustrates the current distribution and the potential graph which would obtain in a bore hole if there are streaming potentials. I am also attaching an experimental potential graph obtained with a model in which I simulated streaming potentials. This graph shows that the potential curve is not flat-topped. While this curve is quantitatively different from Fig. 15-10 it shows definitely two slanted sections *AB* and *CD*. Inasmuch as Wyllie points out that the potential graphs used in his experiments exhibited a flat top, it seems that, if I am right, there could be only negligible streaming potentials.

To summarize, while Wyllie's paper is an important contribution to a better understanding of the potential graph, I do not believe that his experiments are comprehensive enough to permit formulating an opinion on the presence or absence of streaming potentials in bore holes.

AUTHOR'S REPLY TO MR. GUYOD

It would seem that Guyod is completely unable to agree with my conclusions and he outlines rather fully his reasons for disagreement. While it would be foolish to be unduly dogmatic, I nevertheless believe that my conclusions are substantially valid. I will therefore endeavor to deal seriatim with Guyod's objections.

I do not believe it true to say that our knowledge of borehole electrochemical potentials is incomplete in the sense indicated by Guyod. It is true that the detailed mechanism whereby the potential is set up is a complex subject which is bound-up with the whole theory of membrane electrodes. The theory of such electrodes has been discussed at length by many workers since it is not a subject unique in the oil industry; a number of references from the voluminous literature are given in Reference 4 above. It will suffice to say that from the thermodynamical standpoint (which, of course, does not involve reaction mechanisms) the equation for the electrochemical potential across a shale membrane is given by,

$$E = RT/F \; ln \; \frac{a'_{Na}}{a''_{Na}} \quad . \; . \; . \; . \; . \; . \; (1)$$

where a'_{Na} and a''_{Na} are single sodium ion activities. When the shale membrane is included in a circuit which also involves a junction potential, the equation becomes that for a cell with transference and,

$$E = 2t \; RT/F \; ln \; \frac{a'_{NaCl}}{a''_{NaCl}} \quad . \; . \; . \; . \; (2)$$

where a'_{NaCl} and a''_{NaCl} are now the mean ionic activities of sodium chloride solutions and these mean activities are unequivocably determinable from isopiestic or other independent chemical experiments. May I note once again that it is activities that are involved, not resistivities. The use of resistivities instead of activities is a crude approximation only justifiable in very dilute solutions and certainly not permissible in the great majority of electric log calculations.

Equation (2) is a fundamental equation which indicates the maximum emf that can be obtained from a given set of chemical conditions. Equation (2) can be in error for at least two obvious reasons; because muds and connate waters are not pure sodium chloride solutions and because cation exchange between shales and muds is possible. I have recently dealt with these subjects in some detail[1] and there is no need to repeat my argument. In essence it is indicated that if log potentials are observed which are *much greater* than those given by Equation (2), then some source of potential in addition to the electrochemical potential must be operative down the borehole. Certain such cases have been reported (Reference 2 above) and many others observed by us.

I emphasize that potentials much greater than are given by Equation (2) have been observed; potentials less than are given by Equation (2) are frequently seen since such complications as high formation resistivities, deep mud filtrate invasion, dirty formations or even electrochemically inefficient shale formations (apparently rare) will all serve to give a potential lower than that required by Equation (2).

The fundamental question then is: what is this additional source of potential? It may be noted that this additional potential appears to be such as to increase a negative SP kick, although the purist would be justified in saying that this need not be invariably true since an additional potential which served to decrease the conventional negative SP kick could not readily be distinguished from those other factors, outlined above, which also serve to reduce the electrochemical SP.

Guyod indicates that there are many other possible causes of potential, although he does not list them. With such a statement I am by no means in entire agreement. Certain electrochemical cells, such as those operative in the vicinity of chemically reacting ore bodies, do not appear to be operative in most sedimentary rocks. Again, the general constancy of shale base lines indicates that such potentials, if genuine would have to be quite remarkably uniform. A Dorn potential (Reference 1 above) is conceivable, but such a potential should tend only to modify slightly any slope of the shale base line resulting from thermal effects, e.g., a temperature difference, $\triangle T$, across a permeable bed should shift the base line by an amount equal to $2t \; \frac{R \triangle T}{F} \; ln \; \frac{a'_{NaCl}}{a''_{NaCl}}$.

Guyod apparently does not gainsay the fact that an increase in the hydrostatic pressure of a mud column will alter the SP kick observed; in general, a negative SP kick is thereby increased. Guyod ascribes these SP changes to pressure induced changes in electrochemical emf, not to a change in streaming potential, in spite of the fact that both in magnitude and direction laboratory experiments confirm the streaming potential hypothesis.

The effect of pressure changes on Equation (2) resides in the effect that the pressure changes may have on the activities of the connate water and mud, designated a'_{NaCl} and a''_{NaCl} respectively. Such pressure induced changes are negligible as I pointed out in a footnote on the first page of the paper, and thus no measurable change in electrochemical potential is to be anticipated. I cannot, therefore, agree with Guyod when he ascribes potential changes to the effect of pressure on electrochemical emf. (It is not irrelevant to note that the glass electrode will record substantially the same *pH* irrespective of its ambient pressure.) Guyod makes the point that not only is the negative potential increased opposite sands but also, to a lesser degree, opposite shales. I am not altogether clear as to the meaning of this statement since the absolute potential of the shale base line on the log is arbitrary and controlled by the potential difference between the borehole and mud-pit electrodes and any bucking potential between them. What is generally important is the potential difference between contiguous sands and shales and this difference is not affected by variations in the absolute potential of the shale base line. I assume that Guyod means that in the absence of any alteration in bucking potential between the two SP electrodes or movement of the mud-pit electrode, the application of pressure alters the recorded position of the shale base line. This does not seem unreasonable to me if it is recollected that the potential between the two SP electrodes — one down the borehole and one in the mud-pit — can only remain constant if the environmental potential of each electrode (chiefly the contact potential, lead/mud) remains constant.

If one electrode is distorted slightly by pressure, particularly if this pressure is rather suddenly applied, its contact potential may alter owing to slight cracking of the surface film built up by reaction with the mud fluid. Thus, a pressure change, by altering the contact potential of the borehole electrode, could alter the absolute potential of the shale base line but not the potential difference between shale and sand. It is this potential difference which is measured before and after the application of pressure and it is changes in this potential difference which I ascribe to a streaming potential. In support of the above hypothesis I note that when we have used reversible SP logging electrodes of the lead/lead chloride type, little, if any, displacement of the recorded shale base line results from pressure changes.

With regard to the hysteresis effect that Guyod cites, it is, I confess a phenomenon which we have not observed. However, I would not deny its existence since the precise recording of the effect clearly requires deliberate and careful coordination between the operators of the mud pumps and casing-head stuffing box and those recording the log; such exact coordination was never attempted by us and hence we have no data on any hysteresis effects occurring during our experiments. However, hysteresis involving times approximating the 15 to 60 seconds quoted by Guyod was noted in laboratory streaming potential experiments.

Such hysteresis was observed with Mud No. 4 at room temperature and with most muds at elevated temperatures. This effect has been noted in the paper. In general the hysteresis took a form opposite to that observed by Guyod; this is evidenced by Fig. 3 which shows that removal of pressure from 500 psi to 100 psi gave a streaming potential some 2.5 mv lower than the equilibrium streaming potential. Thus, after partial removal of pressure the observed potential slowly increased to its equilibrium value. However, similar potential decreases have been observed, although more rarely. Fig. 4 shows such a case, the potential following a pressure decrease being slightly higher than the equilibrium potential. In general, it may be said that the hysteresis effects observed by Guyod are not incompatible with a streaming potential hypothesis. Certainly no known electrochemical hysteresis effects of the type he observed are known to exist.

I fear that I cannot subscribe to Guyod's views pertaining to the effect of a streaming potential component on the shape of a SP curve. The streaming potential across the filter cake is essentially equivalent to a separation of positive and negative charges and may be compared to an additional junction potential. Since the pressure difference between the hydrostatic head of mud and the bottom-hole pressure is substantially constant even for a thick bed, and since I have shown that the actual filter cake thickness does not affect the streaming potential, the streaming potential is substantially constant over the entire area of a mud cake sheathing off a permeable bed. It is true that current flows across the filter cake to maintain this streaming potential, but the pattern of this current does not in any way resemble that drawn in Fig. 15-10 of the paper quoted by Guyod, the lines of current substantially flowing only across the filter cake itself and not taking the circuitous paths through sand and shale shown in that figure. This is partly because in practical instances the filter cake is extremely thin and therefore its resistance is very small in comparison with any alternative conducting paths through sand and shale beds. In Guyod's model experiment the filter cake thickness is 0.5 for a hole diameter of 1.0; i.e., equivalent to 2½ in. in a 10-in. hole if the more reasonable assumption is made that the filter cake is built up in the borehole and not in the formation. Alternatively in Guyod's experiment the filter cake thickness is 1/16.5 as thick as the bed, leading to a 3-ft thickness of cake in a 50-ft bed. I believe that if Guyod postulates a 1-in. filter cake thickness and a 50-ft. bed, he will find that any "pointedness" of the SP curve will be completely undetectable.

It is also relevant to note that the distribution of resistivity shown in Guyod's figure is improbable. The formation factor of filter cakes is approximately two, whereas the minimum for a formation is five. If there is a filter cake then, ipso facto, there must have been filtrate, and the resistivity behind the filter cake will tend to be (5/2) greater than the filter cake resistivity. In general, as also pointed out elsewhere,[2] the streaming potential component may be regarded as a potential algebraically added to the electrochemical potential which, by causing circulatory electrical current to flow at sand-shale boundaries, gives rise to the SP curve by ohmic effects.

I would like to emphasize that although I clearly disagree with Guyod it is most refreshing to have this fundamental disagreement brought out into the open. Too frequently papers which have controversial conclusions are never adequately queried or even mentioned in subsequent publications on the same subject, thus leading to intolerable confusion in the literature.

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2. Review of Schlumberger Well Logging and Auxiliary Methods, Schlumberger Document No. 2, (1949), pp. 34-35. ★

PRESSURE BEHAVIOR IN THE WOODBINE SAND

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ABSTRACT

A pressure difference of 280 psi measured initially on opposite sides of the major fault in the Hawkins Field led to pressure determinations in the Woodbine sand throughout the East Texas basin. Considering the large area, there is unusually good correlation between pressure losses and points of major withdrawals, these losses indicating that the basin pressure has been materially reduced by withdrawals, primarily from the East Texas Field and secondarily from the old fault-line fields of Limestone and Navarro counties, with the pressure loss varying inversely with the log of the distance from these two main areas of basin withdrawals to the measurement points. Apparently faults located throughout the basin serve as local blocks to continuous pressure gradients.

INTRODUCTION

The pressure anomalies found in the Hawkins Field, Wood County, Texas,[1] shortly after discovery have led to an area-wide investigation of the pressure distribution within the Woodbine sand of the East Texas basin. These pressures were obtained by drill-stem tests made for that sole purpose while drilling wildcat wells to deeper horizons. The Woodbine sand of Gulf Cretaceous Age is or has been productive of oil and gas in 42 different fields, with the 28 oil fields currently active having produced 118,000,000 bbl of oil during 1949. With one exception, producing energy for all Woodbine reservoirs has been from water drive provided predominantly by expansion of the tremendous volume of water contained in the Woodbine sand. This producing mechanism was recognized at an early date and was described mathematically by

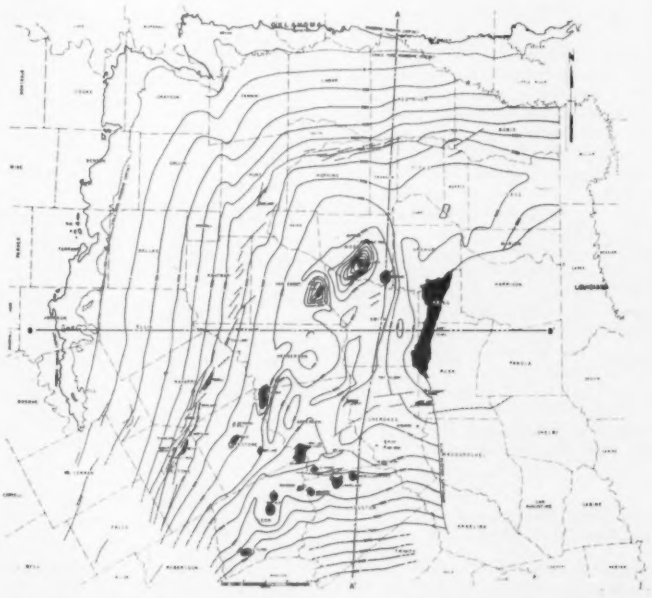

FIG. 1 — STRUCTURE MAP, EAST TEXAS BASIN, CONTOURED ON TOP WOODBINE — 500 FT INTERVAL.

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch Sept. 15, 1950. Paper presented at the 1950 Fall Meeting of the Petroleum Branch in New Orleans Oct. 4-6.

Muskat[2] and by Schilthuis and Hurst[3] in 1934, and these principles were applied to the East Texas Field performance by Buckley[4] in 1938.

Factual data on the pressure behavior in the Woodbine sand, especially in areas non-productive of oil, have been generally lacking, making estimates of pressures at various points within the basin dependent upon mathematical analyses involving numerous assumptions. Such factual data have been gathered and are now presented as possible aid to the industry in further analysis of the producing mechanism in the Woodbine sand.

DISCUSSION

Geology

The Woodbine formation of Gulf Cretaceous Age has been described by R. T. Hill[5] and others as being comprised of thick blanket sands with interbedded shales. Within the East Texas basin, oil and gas, accompanied by water, have been produced from this formation in at least 42 fields, including the huge East Texas Field. These fields resulting from traps caused by faults, domes, and stratigraphic pinchouts are, with one possible exception, afforded a common aquifer by the continuity of the Woodbine formation which, within the recognized bounds of the East Texas basin, covers some 48 counties embracing 31,500 square miles.

A map has been prepared of the East Texas basin area on which are shown Woodbine producing fields in bold relief, major faults in the area as mapped by the Texas Bureau of Economic Geology, and the Woodbine outcrop. Fig. 1 is a copy of this map, on which are shown top-of-Woodbine contours and cross-sectional lines A-A' and B-B'. The Woodbine formation within this large regional trough outcrops to the north and west and is pinched out against the Sabine uplift to the east. Southward the formation plunges with regional dip, becoming much less permeable, and is believed to pinch out. Figs. 2 and 3, depicting generalized east-west and north-south cross sections of the East Texas basin, further illustrate these structural features.

Producing Mechanism of the Woodbine Sand

Table I lists the Woodbine fields which have produced oil and gas in the East Texas basin. It will be noted that although Woodbine production is obtained from some 15 counties in the basin, there have been two main areas of production, the first being the Mexia-Talco fault-line fields in Limestone and Navarro counties and the second, the East Texas Field embracing parts of Cherokee, Gregg, Rusk, Upshur, and Smith counties. The fault-line production began in 1920 with oil discovered in the Mexia Field, Limestone County. It was not until several years after discovery of the East Texas Field that it was realized that a common aquifer existed between the fault-line fields and

Table I — Production Data Woodbine Fields[a]

Field	County	Year of Discovery	Oil Production Thousands of Bbl 1949	Oil Production Thousands of Bbl Cum. 1-1-50
(Active 1-1-50)				
East Texas	Cherokee, Gregg, Rusk, Smith, Upshur	1930	93,527	2,669,230
Hawkins	Wood	1940	11,454	107,842
Van	Van Zandt	1929	8,275	203,274
Cayuga	Anderson, Freestone, Henderson	1934	1,944[b]	43,625[b]
Long Lake	Anderson, Leon, Freestone	1933	1,256[b]	26,313[b]
Mexia	Limestone	1920	379	101,632
Powell	Navarro	1923	359	114,745
East Long Lake	Anderson	1941	229[b]	1,995[b]
Wieland	Hunt	1942	121	941
William Wise	Cherokee	1946	90	353
Wortham	Freestone	1924	81	23,564
Navarro Crossing	Houston	1938	89[b]	1,395[b]
Lone Star	Cherokee	1938	74	703
Pleasant Grove	Rusk	1941	53	591
Boggy Creek	Anderson, Cherokee	1925	44	4,427
Quitman	Wood	1948	35	44
Currie	Navarro	1921	18	7,121
Bazette	Navarro	1939	16	338
Merigale Paul	Wood	1946	12	69
Richland	Navarro	1924	9	6,737
Flag Lake	Henderson	1937	6	658
Tehuacana	Limestone	1940	5	74
Normangee Flynn	Leon	1946	3	12
Cedar Creek	Limestone	1927	3	336
Weches	Houston	1948	3	92
Honest Ridge	Limestone	1946	2	9
Southern Pine	Cherokee	1948	1	4
Grapeland	Houston	1936	218[c]	9,791[c]
Elkhart	Anderson	1938	25[c]	35[c]
Oakwood	Leon	1939	16[c]	76[b]
Buffalo	Leon	1934	24[b]	90[b]
Percilla	Houston	1937	20[c]	145[b]
Reed	Freestone	1947	7[c]	18[b]
Red Lake	Freestone	1934	2[c]	4[c]
Steward's Mill	Freestone	1943	7[c]	16[c]
(Inactive 1-1-50)				
Nigger Creek	Limestone	1926	0	2,999
Rusk	Cherokee	1934	0	261
Rowe & Baker	Henderson	1939	0	82
Manziel	Wood	1946	0	6
Camp Hill	Anderson	1935	x	x
Groesbeck	Limestone	1924	x	x
Sessions	Cherokee	1948	0	0
Total			118,020	3,309,788

[a] Data from "Development and Production in East and East Central Texas in 1949," *Statistics of Oil and Gas Development and Production for 1949.*
[b] Includes oil and condensate.
[c] Condensate production.
[x] Information not available.

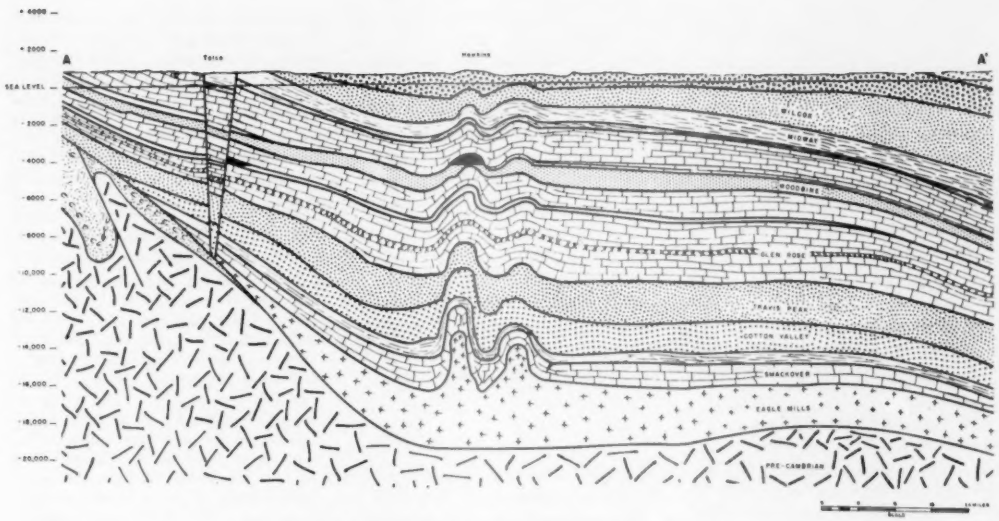

FIG. 2 — CROSS SECTION, EAST TEXAS BASIN — NORTH-SOUTH SECTION A-A'.

the East Texas and Van fields and that the production from a given field in the Woodbine reservoir could influence pressures elsewhere in the basin. In 1934, Muskat in an issue of *Physics*[2] and Schilthuis and Hurst in an AIME paper[3] described the producing mechanism in the East Texas Field, showing the pressure-production performance there to be governed primarily by the expansibility of the large volume of water contained within the Woodbine formation throughout the basin. Again in 1938, Buckley in an API paper[4] reviewed the East Texas Field producing mechanism and presented calculations demonstrating that the rate of availability of water by expansion was limited and that sound production practices in the nature of controlled net water production would be required in the East Texas Field to prevent loss in ultimate oil recovery.

Despite such early recognition that the Woodbine formation provides a common aquifer for its many water-drive fields and that the pressure in this aquifer would decline with production, factual data on the pressure behavior, particularly in areas non-produc-

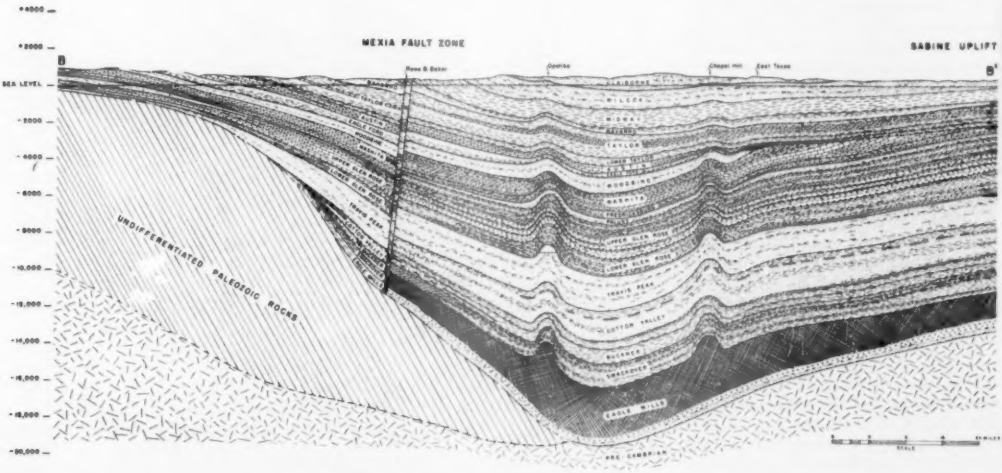

FIG. 3 — CROSS SECTION, EAST TEXAS BASIN — EAST-WEST SECTION B-B'.

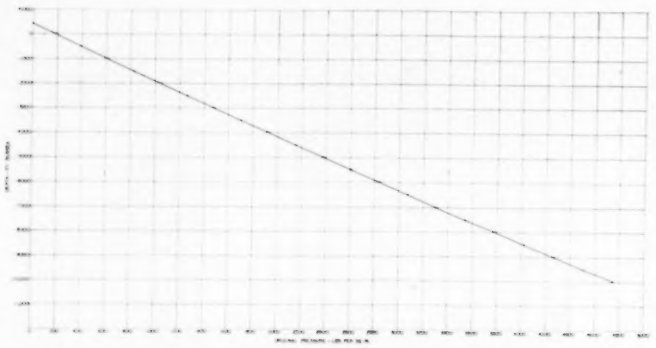

FIG. 4 — ORIGINAL PRESSURE VS. SUBSEA DEPTH, WOODBINE SANDS.

tive of oil, have been generally lacking. Consequently, estimates of pressure at points removed from producing fields have been largely dependent on mathematical calculations which necessarily required numerous assumptions.

Pressure Anomalies in the Hawkins Field

Shortly after discovery of production from the Woodbine sand in the Hawkins Field[1] in December, 1940, it was determined that a major northeast-southwest fault divided the field into two parts. Detailed pressure surveys within the field showed the original pressure in the eastern part of the Hawkins structure to be 1,710 psi corrected to a subsea depth of 4,075 ft; while in the western part of the field, an original pressure of 1,990 lb corrected to the same subsea depth was observed. In attempting to explain this phenomenon, three possibilities were considered: first, that the pressure in East Hawkins was the normal pressure, the West Hawkins pressure being abnormal due to compaction or extraneous force brought on by the extreme faulting; second, that the 1,990 lb in West Hawkins reflected the relative pressure in the water surrounding the field and that East Hawkins was in effect a closed reservoir, the oil being separated from water by some impermeable barrier, and that some pressure had dissipated upward from East Hawkins through fault planes; or, third, that West Hawkins was a closed reservoir, the oil and water being separated by an impermeable barrier, and that the pressure in East Hawkins had equalized or was equalizing with the pressure in the water surrounding the structure.

By visual observation and laboratory examination of cores and by production tests, it was found that the gas-oil and water-oil contacts in East Hawkins were both considerably lower than in West Hawkins, where a heavy asphalt deposit averaging some 40 ft in thickness was found at the base of the producible oil column. Comparisons with pressure information from other Woodbine-producing fields also revealed that the pressure in West Hawkins approached what would have been considered a normal original pressure for its depth. The third assumption was accordingly considered correct, the conclusion being that the initial pressure in East Hawkins was some 280 lb below normal because of East Texas Field withdrawals made during the 10-year period prior to Hawkins discovery.

The interesting pressure relation of East and West Hawkins and the East Texas Field prompted an area-wide study to determine the effect the withdrawals from the East Texas Field had had upon the general pressure in the Woodbine sands. Since 1942, Humble Oil and Refining Co. in its wildcat program within the area has measured the pressure in clean porous water-bearing sands of the Woodbine formation in 57 wells located in 18 counties. The pressures used in this paper were measured during drill-stem tests in which the tool was kept open long enough to assure stabilized static conditions, and pressures were checked in most tests by comparing pressures measured down the drill pipe with pressures obtained by a gauge below the testing tool.

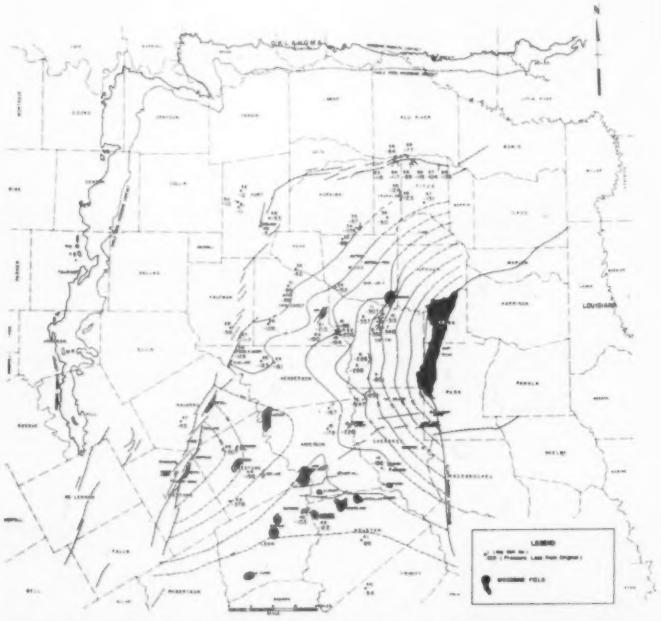

FIG. 5 — PRESSURE LOSS MAP, WOODBINE FORMATION. CONTOUR INTERVAL — 50 PSI.

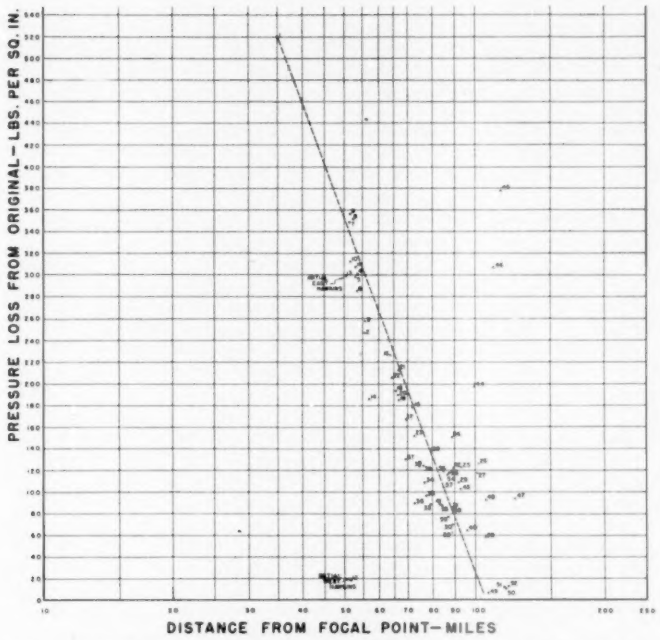

FIG. 6 — PRESSURE LOSSES, ALL WELLS, TOTAL INFLUENCE FOCAL POINT — EAST TEXAS FIELD.

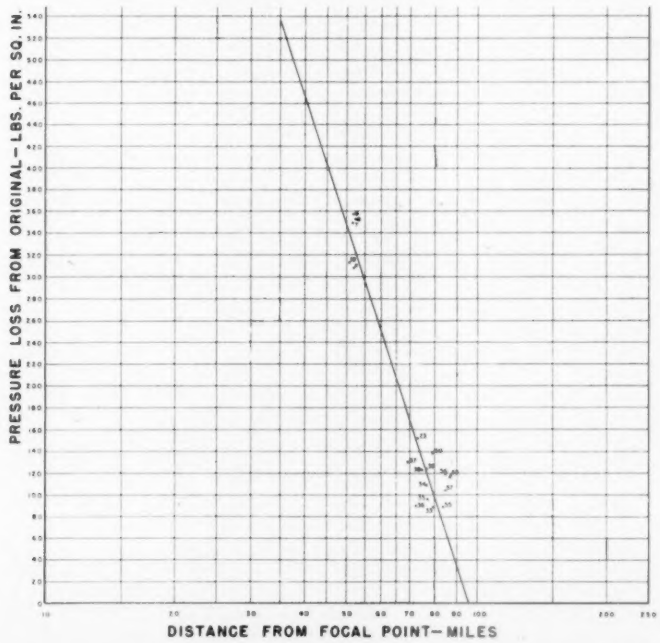

FIG. 7 — PRESSURE LOSSES, WELLS INFLUENCED ONLY BY EAST TEXAS FIELD FOCAL POINT, EAST TEXAS FIELD.

Estimated Original Woodbine Sand Pressures

In order to evaluate the pressures obtained in terms of loss from the estimated original pressures rather than making it necessary to correct all pressures to a given datum, the curve shown by Fig. 4, "Original Pressure versus Subsea Depth, Woodbine Sand," was constructed. This relationship was derived from the integration of a curve representing measured density values versus subsea depths where densities had been corrected for varying water compressibility and formation temperature. The average elevation of the outcrop of the Woodbine formation was determined to be 423 ft by extrapolating to zero pressure a curve of original observed pressure versus subsea depth for Van, East Texas, West Hawkins, Navarro Crossing, Well No. 50 (Lessa Norman 1, Hunt County), and Well No. 41 (C. W. LeGory 1, Houston County).

Distribution of Pressure Loss

Table II shows the calculated original pressures, the measured pressures, and the indicated pressure loss on each of these tests, as well as the date, location, depth of test, and distance from Points *X* and *Y*, which were used in establishing pressure loss—log distance relationships. Fig. 5 is the base map of the East Texas area, on which are shown locations of the test wells, indicated pressure drops from estimated original pressures, and contours of pressure losses. These contours, developed in the conventional manner of straight-line interpolation between actual measurement points, demonstrate that East Texas Field withdrawals have been the major cause of pressure losses in the basin, although fault-line field withdrawals have contributed significantly to such losses. Several unusual configurations which may be noted on the map encouraged a further effort to interpret the data. Considering radial flow principles, it was concluded that these pressure losses should vary with the log of their distance from a point representing a hypothetical focal point of withdrawals from each of the two major areas. This led to the construction of Fig. 6, which is a plot of the pressure loss versus log distance from a point labeled *X*, representing East Texas Field withdrawals, located at the intersection in Panola County of a 20.4-mile arc drawn from the southwest corner and a 12.3-mile arc drawn from

the northwest corner of that county. All pressure losses are included on this plot, which indicates a general straight-line trend. This trend is interpreted to indicate further that the East Texas Field withdrawals have been the dominant influence on the pressure behavior within the basin. For illustrative purposes, the original pressures in East and West Hawkins have been corrected to 4,470 ft subsea, and estimated pressure losses have been plotted on the curve. This shows further that of the two pressures, the one measured in West Hawkins was the one abnormal at the time.

In addition to the abnormal West Hawkins pressure, it is noted that some other points fail to correspond satisfactorily with the trend. Considering this probably due to the influence of fault-line production, an effort was made to isolate those points of pressure measurement which were influenced predominantly by only East Texas Field withdrawals. Fig. 7 is a plot comparable to Fig. 6 except that measurements apparently influenced by fault-line production or those shown to be influenced by local fault conditions have been removed. On Fig. 7, indications are that East Texas Field withdrawals have affected pressures for a distance of 65 miles from the field or nearly 100 miles from the imaginary focal point, *X*.

A plot, Fig. 8, was made of pressure loss versus log distance of only those points whose pressure loss resulted solely from fault-line field production, with the hypothetical focal point labeled *Y* located in Limestone County at the intersection of a 5.9-mile arc drawn from the northeast corner and a 32.4-mile arc drawn from the southeast corner of that county. Fig. 8 suggests that the maximum distance of influence of fault-line field production has been approximately 80 miles from Point *Y*. Having separated the indicated pressure loss influence of fault-line field production from that of East Texas Field production, as represented by Fig. 7 and 8, Fig. 9 was then constructed, which corrected points jointly influenced by withdrawals from both areas, showing only the indicated influence of East Texas withdrawals. The accuracy of the corrections made for fault-line field production influence is indicated by the fact that the average curve on Fig. 9, the plot of distance from Point *X* versus pressure losses corrected for fault-line field production interference, corresponds to the average curve on Fig. 7, the plot of distance from Point *X* versus pressure losses not influenced by fault-line field production.

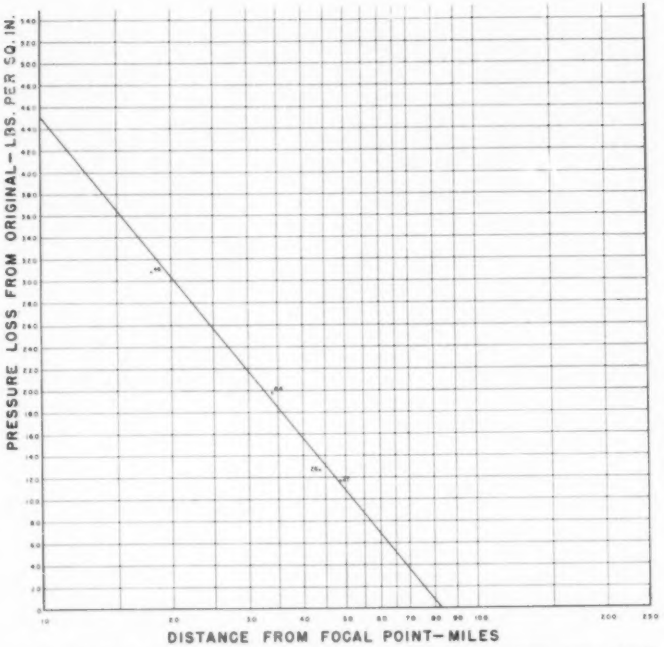

FIG. 8 — PRESSURE LOSSES, WELLS INFLUENCED ONLY BY FAULT-LINE FIELDS FOCAL POINT, FAULT-LINE FIELDS.

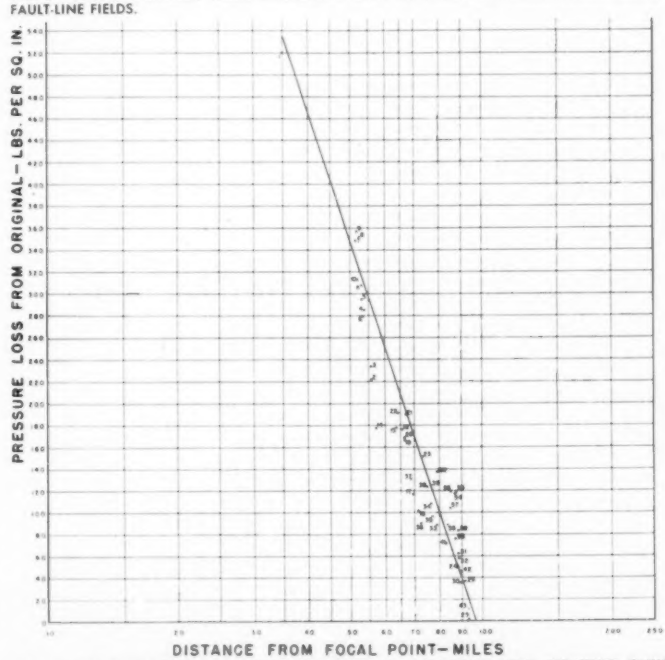

FIG. 9 — PRESSURE LOSSES, ALL WELLS, CORRECTED TO EAST TEXAS FIELD INFLUENCE ONLY FOCAL POINT, EAST TEXAS FIELD.

Fig. 10 is the same map as Fig. 5 except that Points *X* and *Y* are located and arcs have been drawn from these points representing the limit of influence of withdrawals from the East Texas Field and fault-line fields. The area which is affected by withdrawals from both of these sources is cross-hatched. The unusual contour configurations noted, particularly in Van Zandt, Henderson, and Anderson counties, are in this cross-hatched zone. The contour drawn into the Hawkins Field is a result of drainage restrictions caused by the major fault in that field. A few pressure losses indicated on the map vary considerably from those which would be expected; however, some of these variations may be explained by the time over which the pressures were measured, and unknown structural and stratigraphic conditions. Elsewhere it is considered that there is unusually good agreement with the contours and the indicated pattern developed from the pressure loss — log distance relations. Considering the large area involved, there are remarkably few measurements which fail to conform to the expected pattern.

Pressure Behavior Across Faults

In the process of analyzing pressure trends and differences, it has been noticed that pressures on opposite sides of faults quite often show anomalies which indicate a barrier or restriction to drainage across the faults. Specific illustrations of this fact are:

1. in the area of the fault-line fields where the pressure loss in Well No. 47 (B. L. Davis 1, Navarro County) west of the fault line is 95 lb, as compared to a pressure loss east of the fault of 307 lb in Well No. 46 (B. C. Whatley 1, Freestone County);

2. in southeast Kaufman County where Well No. 28 (Lon Hale 1) west of the fault line has a pressure loss of 58 lb as compared to a pressure loss of 117 lb east of the fault line in Well No. 27 (E. N. Rylie 1); and

3. in the area of the Talco Field where the indicated pressure loss of approximately 118 lb basinward from the fault compares with an average loss of 80 lb on the outward side of the fault.

In addition to the unusual configura-

Table II — Pressure in the Woodbine Sand — East Texas Geosyncline

Key No.	Well Name	Field or Area	County	Date of Test	Elevation	Depth Section Tested-Ft Subsurface From	Subsurface To	Subsea From	Subsea To	Depth of Pressure Measurement-Ft Subsurface	Depth of Pressure Measurement-Ft Subsea	Pressure at Measurement Depth-psi On Test Date	Pressure at Measurement Depth-psi Original	Pressure at Measurement Depth-psi Indicated Loss	Distance From Focal Points, Miles X	Distance From Focal Points, Miles Y
1	1100′ Contour	East Texas		1- 1-44	....	....	....	....	....	....	3,324	1,108	1,628	520	35.0	105.9
2	S. T. Stanley 1	Larissa	Cherokee	8-20-44	414	5,389	5,471	4,975	5,057	5,466	5,052	2,158	2,405	247	55.5	73.2
3	W. H. Stephens B-1	Larissa	Cherokee	7-12-44	479	5,760	5,780	5,281	5,301	5,761	5,282	2,252	2,510	258	58.7	73.2
4	Kate E. Sackett 1	Bullard	Smith	5-20 and 21-48	553	5,561	5,630	5,008	5,077	5,622	5,069	2,112	2,413	301	53.6	76.5
5	E. M. Sherlock 1	Tyler	Smith	2- 1-49	570	5,673	5,695	5,103	5,125	5,686	5,116	2,137	2,435	298	53.0	80.3
6	F. Watson 1	Tyler	Smith	8- 4-49	573	5,708	5,746	5,135	5,173	5,742	5,169	2,175	2,460	285	53.4	79.8
7	B. S. Shamburger 1	Sand Flat	Smith	3-24-44	582	5,557	5,645	5,025	5,113	5,641	5,109	2,084	2,433	349	51.2	88.5
8	Roosth & Genecov 1	Sand Flat	Smith	8-31-45	443	5,122	5,163	4,679	4,720	5,159	4,716	1,902	2,254	352	52.1	88.2
9	P. K. Birdwell C-1	Sand Flat	Smith	12- 7-48	437	5,197	5,220	4,760	4,783	5,215	4,778	1,925	2,282	357	51.7	90.0
10	H. E. Kidd 1	Sand Flat	Smith	9-19-47	482	5,627	5,670	5,145	5,188	5,659	5,177	2,150	2,463	313	51.9	90.3
11	E. W. Winttters 1	Red Springs	Smith	6- 5-48	536	5,500	5,571	4,964	5,035	5,562	5,026	2,089	2,396	307	53.0	91.5
12		East Hawkins	Wood		12-40	(Discovery Date)					4,470	1,844	2,142	298	51.3	98.4
13		West Hawkins	Wood		12-40	(Discovery Date)					4,470	2,124	2,142	18	52.8	97.2
14	New Birmingham Dev. Co. 1	Fastrill	Cherokee	4- 4-45	441	5,490	5,500	5,049	5,059	5,485	5,044	2,216	2,402	186	57.9	79.2
15	W. T. Todd 1	Boggy Creek	Anderson	9-29-45	300	4,645	4,750	4,345	4,450	4,745	4,445	1,906	2,132	226	63.6	65.6
16	R. G. Freeman 1	Brushy Creek	Anderson	11-16-45	562	5,290	5,350	4,728	4,788	5,346	4,784	2,106	2,285	179	71.9	57.2
17	T. O. Milner 1	Fosterville	Anderson	8- 7-48	508	5,646	5,711	5,138	5,203	5,707	5,199	2,305	2,472	167	69.5	59.3
18	T. J. Pool 1	Mt. Sylvan	Smith	11- 9-45	454	5,644	5,675	5,190	5,221	5,671	5,217	2,286	2,480	194	65.7	75.3
19	H. R. Dowell 2	Mt. Sylvan	Smith	7- 6-48	434	5,809	5,820	5,165	5,186	5,818	5,182	2,280	2,465	185	66.5	75.9
20	Frank Woods 1	Mt. Sylvan	Smith	2-22-47	416	5,534	5,585	5,118	5,169	5,580	5,164	2,267	2,457	190	66.3	74.1
21	Perk Beasley 1-S	Mt. Sylvan	Smith	5-12-48	442	5,343	5,442	4,901	5,000	5,884	5,442	2,372	2,585	213	66.9	74.0
22	M. L. Gary 1	Boynton	Smith	4-28-47	448	5,505	5,560	5,057	5,112	5,555	5,107	2,226	2,432	206	64.2	76.7
23	H. Watts 1	Nolan Edwards	Wood	12- 9-49	388	5,779	5,794	5,391	5,406	5,791	5,403	2,415	2,567	152	72.6	84.6
24	W. J. Benge 1	Stockard	Henderson	12-11-46	455	4,691	4,710	4,236	4,255	4,705	4,250	1,855	2,044	191	88.1	51.0
25	A. G. Jones 1	Eustace	Henderson	1- 8-45	377	4,327	4,372	3,950	3,995	4,363	3,986	1,803	1,926	123	93.0	46.2
26	J. Burford 1	Mabank	Henderson	7-24-50	362	3,949	3,983	3,587	3,621	3,973	3,611	1,630	1,756	126	102.2	43.7
27	E. N. Rylie 1	Ham Gossett	Kaufman	11-30-48	375	3,806	3,826	3,431	3,451	3,843	3,446	1,565	1,685	117	101.4	48.8
28	Lon Hale 1	Kemp	Kaufman	7-30-46	409	3,455	3,470	3,046	3,061	3,465	3,056	1,450	1,508	58	105.6	50.1
29	E. E. Lutz 1	West Jackson	Van Zandt	11-15-45	477	4,570	4,595	4,093	4,118	4,591	4,114	1,873	1,982	109	91.7	58.7
30	B. W. Bruce, Jr. 1	Myrtle Springs	Van Zandt	8-10-44	510	4,622	4,700	4,112	4,190	4,696	4,186	1,946	2,015	69	89.0	70.1
31	Joe Surratt 1	Edgewood	Van Zandt	4-26-44	440	4,579	4,605	4,139	4,165	4,605	4,165	1,919	2,005	86	88.6	73.8
32	D. B. Mainard 1	Emory	Rains	12-22-43	375	4,590	4,621	4,215	4,246	4,575	4,200	1,958	2,020	62	88.5	80.6
33	Rio Oil Corporation 1	Yantis	Wood	5-12-47	398	4,406	4,861	4,008	4,463	4,853	4,455	2,047	2,136	89	79.1	99.5
34	P. T. King 1-S	Pickton	Hopkins	2-13-47	470	4,900	5,200	4,430	4,730	5,200	4,730	2,151	2,260	109	76.1	106.2
35	C. D. Nichols 1	Pickton	Hopkins	7- 1-44	472	4,912	4,930	4,440	4,458	4,926	4,454	2,039	2,136	97	77.0	106.8
36	Solon King 1	Scroggins	Franklin	11-23-43	370	4,550	4,600	4,180	4,230	4,513	4,143	1,906	1,996	90	72.3	116.1
37	C. C. Searcy 1	Mt. Pleasant	Titus	6- 9-44	398	4,367	4,441	3,969	4,043	4,250	3,852	1,733	1,864	131	69.3	129.3
38	J. F. Hague 1	Winfield	Franklin	4-26-44	422	4,160	4,170	3,738	3,748	4,164	3,742	1,693	1,816	123	74.7	124.2
39	Angelina Jaggears 1	Winfield	Franklin	10-18-46	433	4,159	4,210	3,726	3,777	4,205	3,772	1,703	1,827	124	76.2	95.0
40	Thompson Bros. Min. Corp. 1	Glendale	Trinity	8-2 to 8-48	184	9,525	9,555	9,351	9,371	9,555	9,371	4,380	4,444	64	96.2	85.8
41	C. W. LeGory 1	Crockett	Houston	8-25-46	385	7,518	7,536	7,133	7,151	7,536	7,146	3,291	3,340	49	83.0	75.9
42	C. C. Hill 2	Navarro Crossing	Houston	1- 9-46	272	6,052	6,099	5,780	5,827	6,092	5,820	2,636	2,758	122	89.6	57.6
43	Leone Plantation 1	Oakwood	Leon	7-18-45	264	5,900	5,917	5,636	5,653	5,895	5,631	2,567	2,670	103	92.4	53.3
44	G. J. Weaver 1	Red Lake	Freestone	6- 4-46	405	4,808	4,838	4,403	4,433	4,808	4,403	1,915	2,113	198	99.3	33.9
45	R. P. McWatters 1	Teague	Freestone	8-26-47	489	4,763	4,775	4,274	4,286	4,770	4,281	1,680	2,058	378	114.9	18.0
46	B. C. Whatley 1	Kirvin	Freestone	2-11 & 12-48	406	3,780	3,830	3,374	3,424	3,830	3,424	1,367	1,674	307	111.0	19.0
47	B. L. Davis 1	Corbet	Navarro	6-8 and 9-48	351	2,237	2,253	1,886	1,902	2,246	1,895	995	1,090	95	123.9	12.0
48	R. P. Barnett 1	South Dixon	Hunt	5-26-48	466	3,508	3,550	3,044	3,086	3,545	3,081	1,431	1,524	93	105.9	92.3
49	Aetna Life Ins. Co. 1	Wieland	Hunt	7-19-42	497	2,823	2,832	2,326	2,335	2,815	2,318	1,183	1,188	5	107.1	88.5
50	Lessa Norman 1	Greenville	Hunt	2- 2-44	559	2,460	2,500	1,901	1,941	2,466	1,907	995	1,005	10	118.7	93.9
51	J. A. Rutherford 1	Greenville	Hunt	11-22-43	540	2,550	2,590	2,010	2,050	2,547	2,007	1,038	1,049	11	117.5	92.1
52	E. M. Anderson 1	Kingston	Hunt	4- 1-44	599	2,130	2,150	1,531	1,551	2,148	1,549	841	853	12	119.9	98.1
53	P. J. Dawson 2-S	Talco	Franklin	4-28-48	374	3,224	3,381	2,850	3,007	3,381	3,007	1,370	1,488	118	87.3	133.2
54	Lena Wims 1-S	Talco	Franklin	11- 9-46	356	3,613	3,702	3,257	3,346	3,700	3,344	1,522	1,639	117	86.8	133.8
55	Hoffman Fee 1-S	Talco	Titus	8- 2-42	311	3,356	3,500	3,045	3,189	3,366	3,055	1,419	1,508	89	83.8	136.2
56	A. W. Batson 1-S	Talco	Titus	12- 2-47	361	3,199	3,397	2,838	3,036	3,397	3,036	1,379	1,498	119	84.7	137.4
57	E. L. Riddle 4-S	Talco	Titus	5-13-44	330	3,212	3,262	2,882	2,932	3,262	2,932	1,349	1,453	104	84.4	147.9
58	T. C. Geron 1	Sulphur River	Franklin	9-20-45	321	3,630	3,713	3,309	3,392	3,708	3,387	1,574	1,658	84	88.5	134.1
59	Guaranty Bond 1	Sulphur River	Titus	9-19-46	313	3,716	3,767	3,403	3,454	3,762	3,449	1,608	1,685	77	86.9	137.7
60	P. H. Pewitt 1	Pewitt Ranch	Titus	11-23-49	278	3,631	3,649	3,353	3,371	3,644	3,366	1,512	1,650	138	79.4	143.1

tions of the contours caused by additive influence of East Texas Field and fault-line field withdrawals, it is noted in a few areas, particularly about the Hawkins Field in Wood County, that local faults within the basin have caused some irregularity in the expected contour behavior. The anomalies in expected pressure behavior resulting from these faults merely serve to point out that the pressure drop is a function of the difficulty and distance of water travel which is greater because of interference in fault areas.

Fig. 11 is a map of the Hawkins Field on which are shown the major fault dividing the field into West and East Hawkins, and pressures taken below the asphalt barrier at various points in West Hawkins, corrected to March 1, 1946. Table III gives data pertinent to those pressure measurements showing the corrections made to 4,470 ft subsea and the extrapolations made to bring the observed pressures to a common date. It will be noted from the figure that across the northern sector of the West Hawkins reservoir there is a pressure difference of approximately 50 lb running northwesterly, from the Esparcia Survey to the Crane Survey. To the south a pressure difference running southeasterly in the amount of approximately 60 psi is indicated from the Esparcia Survey to the Brewer Survey. These gradients over distances less than four miles appear considerable; however, examination of Fig. 9, the plot of distance from Point *X* versus pressure loss for all wells corrected to East Texas Field influence only, indicates that at this distance from the East Texas Field a gradient of approximately 10 lb per mile is normal. Hence, the pressure differentials measured across the West Hawkins Reservoir are normal. However, illustrative of the effect of fault influence on pressure behavior is a comparison of the 1,859-lb H. E. Watson Survey pressure measured in the West Hawkins water zone and a 1,739-lb average water-zone pressure shown for East Hawkins. The 120-lb differential measured within less than a mile distance on opposite sides of this major fault would normally be expected over a distance of 13 miles.

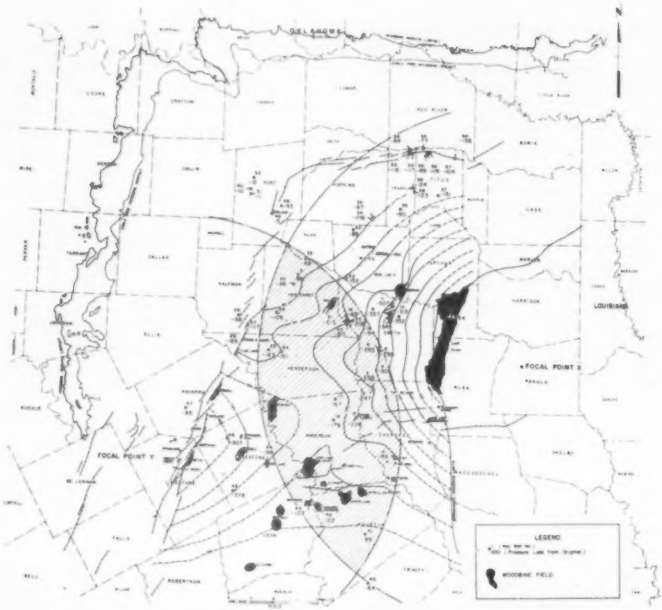

FIG. 10 — PRESSURE LOSS MAP, WOODBINE FORMATION. CONTOUR INTERVAL — 50 PSI SHOWING SPHERES OF INFLUENCE BY MAJOR PRODUCTION AREAS.

Table III — Woodbine Sand Pressures in and Near Hawkins Field

Lease and Well No.	Elev. Ft	Date of Test	Depth Section Tested-Ft Subsurface From	Subsurface To	Subsea From	Subsea To	Depth Pressure Measurement Ft Subsurface	Subsea	Measured Pressure psi	Pressure Corrected 4,470-ft Subsea psi On Test Date	Extrapolated To 3-1-46
L. A. Bryan B-15	449	8-16-46	4,974	5,000	4,525	4,551	4,969	4,520	1,913	1,890	1,893
A. Crisman 2	410	4-26-46	4,986	5,007	4,576	4,597	5,002	4,592	1,961	1,905	1,906
Lillian Eagle 1	392	3- 6-47	5,080	5,112	4,688	4,720	5,105	4,713	2,020	1,909	1,916
E. M. Faulk 8	434	5- 6-46	4,925	4,953	4,491	4,519	4,948	4,514	1,911	1,891	1,892
E. M. Faulk B-4	471	1- 5-46	4,990	5,018	4,519	4,547	5,013	4,542	1,893	1,860	1,859
M. Greines, Jr. 2	471	3-31-47	5,058	5,077	4,587	4,606	5,070	4,599	1,925	1,866	1,873
B. Hargett 4	385	11-28-45	4,893	4,911	4,508	4,526	4,906	4,521	1,864	1,841	1,839
Jackson-Chism B-1	398	3-22-46	4,936	4,955	4,538	4,557	4,950	4,552	1,907	1,870	1,870
P. H. McKnight 1	358	7- 7-46	5,000	5,052	4,642	4,694	5,047	4,689	1,970	1,870	1,872
W. T. Minshew 3	398	3-15-46	4,908	4,919	4,510	4,521	4,916	4,518	1,874	1,852	1,852
Oscar Mitchell 1	408	1- 3-47	4,855	4,915	4,447	4,507	4,910	4,502	1,850	1,835	1,841
Joe Palmer B-2	408	3-23-46	4,919	4,949	4,511	4,541	4,944	4,536	1,879	1,849	1,849
G. R. Philips 1	427	7- 7-47	5,041	5,054	4,614	4,627	5,049	4,622	1,960	1,891	1,898
F. B. Ponder C-3	423	11- 1-45	4,932	4,939	4,509	4,516	4,945	4,522	1,912	1,888	1,886
J. H. Ponder 6	383	3-26-46	4,910	4,933	4,527	4,550	4,928	4,545	1,887	1,853	1,853
R. Price 4	367	12- 1-45	4,880	4,898	4,513	4,531	4,893	4,526	1,860	1,834	1,832
I. Rutherford 6	372	1- 4-46	4,880	4,890	4,508	4,518	4,887	4,515	1,881	1,860	1,859
W. J. Shamburger 2	431	4-19-46	4,928	4,954	4,497	4,523	4,949	4,518	1,900	1,878	1,878
W. S. Shamburger B-4	447	2- 8-46	5,020	5,076	4,573	4,629	5,071	4,624	1,966	1,896	1,895
T. C. Snow 5	422	12- 2-45	4,921	4,944	4,499	4,522	4,939	4,517	1,881	1,860	1,858
T. C. Snow 6	466	7-18-46	4,962	4,981	4,496	4,515	4,976	4,510	1,879	1,861	1,863

CONCLUSIONS

1. Fluid withdrawals from the Woodbine formation in the East Texas basin, particularly from the East Texas Field and from the fault-line fields, have caused pressure loss in practically all of the East Texas basin contained within the Mexia-Talco fault line.

2. The distribution of this pressure loss is in general relation to the log distance from the two main areas of basin withdrawal.

3. Some of the observed irregularities in anticipated pressure patterns are the result of fault interference.

4. The anticipated initial pressure of any new Woodbine field or any long-range forecast of the pressure behavior in any Woodbine field must consider the over-all pressure pattern in the basin.

5. The apparent reasonableness of this qualitative study indicates that regional pressure investigations as well as local field measurements have practical application.

ACKNOWLEDGMENTS

The authors wish to thank Humble Oil and Refining Co. for making the data included in this report possible by allowing the extensive drill-stem testing program and for permission to publish this information. The authors also express their gratitude for and acknowledge the assistance given by the following Humble personnel: Stuart E. Buckley and the Production Research Division, for their encouragement and aid; members of the Exploration Department and Petroleum Engineering Division, and all the associated groups in the East Texas Division of the Production Department.

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DISCUSSION

By William Hurst, Consultant, Houston, Tex., Member AIME

This is a timely presentation of the excellent paper on "Pressure Behavior in the Woodbine Sand," by John S. Bell and J. M. Shepherd. This reviewer has often wondered when such a paper would be forthcoming as he has never accepted that the infinite effect of radial water encroachment into the East Texas Field would continue indefinitely without encountering the interference of withdrawals from the Woodbine basin by existing fields such as Van, Hawkins, and the Mexia-Talco Fault-Line fields.

In order that there may be no illusion as to the validity for treating the Woodbine formation as an infinite aquifer, as interpreted by the original investigators, it suffices only to inform the reader that no matter what form of water-drive is encountered in a reservoir, that will eventually be affected by interference, the formation will essentially behave as an infinite aquifer until such condition is met. That this has been sustained as late as 1944, or 14 years after the inception of East Texas, is verified by this reviewer's study of the field. Beyond this date he has no further knowledge of the status of the field. Nevertheless, from an examination of Figs. 5 and 10 of this paper, the small pressure loss of from 150 to 200 psi, represented by the region of interference in Henderson and Anderson counties, as compared with the significant loss of 500 psi in the vicinity of the East Texas Field, may even to this time justify the analysis for infinite water-drive into East Texas.

If and when geology and geophysics adequately define the limits of an aquifer, the reservoir engineer can incorporate such limitations in the analytical treatment of the formation. Until such evidence is forthcoming the factual field data will have to provide the information, which is the direction that this problem has taken. There are no unforeseeable difficulties contained in the present interference pattern of the Woodbine formation that cannot be treated analytically. This has been amply provided for in the literature, thanks to the contribution of people engaged in the oil industry. Particularly is this point stressed, because the conformity of the pressure pattern due to the voidage of the aquifer by the existing fields and the depletion of the Woodbine as a whole, is most realistically sustained by mathematical deduction for the mechanics of fluid flow.

In this respect, the specialist has reached that phase of translating engineering into dollars and cents for management. It is fitting to remind you that this progress is not of recent date, but took place in East Texas approximately 20 years ago. The material benefits to the community, the accrued and continued income received by the major, independent, and royalty owner over the years, testify to the vision and fortitude of these early investigators in simulating the performance for the res-

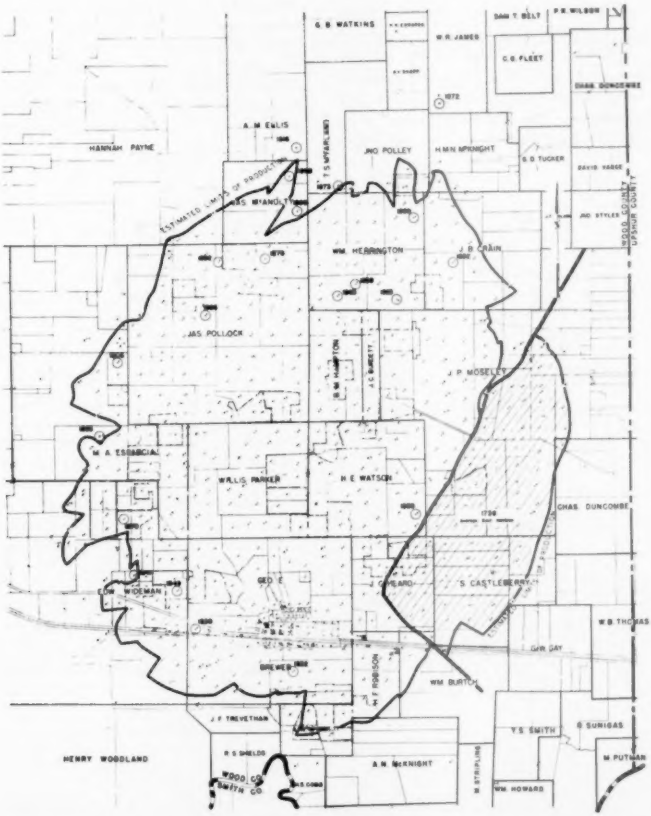

FIG. 11 — WATER ZONE PRESSURE MAP, HAWKINS FIELD, DATUM 4,470 FT SUBSEA. EFFECTIVE DATE, MAR. 1, 1946.

ervoir that today sustains pressure maintenance in the East Texas Field that will assure the continuation of revenue into the future.

To conclude this review, it is recognized that the transient state of pressure change should also have an effect in the interpretation of the interference pattern shown in Fig. 10. Since the compilation of pressures, Table II, is representative from 1942 to the present, the question asked the authors is, has it been possible to make this distinction in the analysis with the data on hand?

DISCUSSION

By M. Muskat, Gulf Oil Corp., Member AIME

The authors are to be congratulated on this excellent paper and their making the results of their study available to the industry. Drill stem testing in wildcat wells for the sole purpose of determining pressures in a locally unproductive formation reflects a most progressive long-range research policy.

The water expansibility theory, as first applied to the East Texas Field, has been accepted as the basis for explaining the water drive performance of many of our major reservoirs. It has served to predict the pressure history of the East Texas Field with remarkable precision over a period of 20 years. Yet, this theory has other important implications with respect to the pressure reaction in the Woodbine aquifer itself, the confirmation of which would be an important factor in the overall evaluation of the water drive oil producing mechanism. The present paper provides just the type of data required for this supplementary analysis.

As noted in the paper, the reported pressure data show the long range pressure reactions to be expected in continuous and permeable fluid bearing porous media. Their correlation with the fluid withdrawals from other fields, as well as East Texas, in the Woodbine sand should settle once and for all the arguments about physically limited drainage radii in permeable continuous reservoirs. The apparent pressure anomalies found across faults also give a gratifying confirmation of the implications of fluid flow concepts generally accepted in explaining oil reservoir performance. The observed large scale shielding effects of impermeable fault barriers is a simple corollary of the compressible liquid flow mechanism, which is even more clearly demonstrated here than in pressure patterns about faults within producing fields.

Recognition and acceptance of the possibility of regional pressure interference in continuous aquifers will facilitate the interpretation and understanding of initial pressure conditions in newly-discovered fields. As also observed elsewhere, this fact will serve to resolve anomalies in pressure histories of fields assumed to react only to their own withdrawals. It may provide explanations in some cases of apparent tilting of water tables. Other applications will undoubtedly develop from a study of the data.

No doubt the authors or their associates will make a quantitative analysis of the pressure observations by the electrical analyzer or similar techniques. It should be especially instructive to determine the quantitative correlations of the data with the theoretical predictions; and it will be interesting to see the implications of such an analysis with respect to the macroscopic expansion capacity of the Woodbine aquifer as well as its gross effective permeability. ★ ★ ★

A STUDY OF THE DORNICK HILLS-SPRINGER SAND RESERVOIR, VELMA POOL, OKLAHOMA

W. B. DAVIS, GULF OIL CORP., TULSA, OKLA., MEMBER AIME

ABSTRACT

This paper presents a summary of the results of a study of the Dornick Hills-Springer sand reservoir of the Velma Pool, Stephens County, Oklahoma. The data are of interest because this type of reservoir is unusual in the mid-continent area.

The reservoir is characterized by very steep dips and a relatively thick producing section. Its up-dip productive limit is defined by truncation of the productive sands, and the down-dip limit is defined by deterioration of sand quality rather than by the presence of an oil-water contact. The crude oil is of 29° API gravity, is relatively viscous and was saturated with dissolved gas at the original reservoir pressure.

Consideration of the physical characteristics of the reservoir indicates that natural water encroachment will be negligible, and that the producing mechanism will be a dissolved gas drive augmented by gravity drainage. Performance to date tends to confirm this.

[1]References given at end of paper.

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INTRODUCTION

It is the purpose of this paper to present some of the features of the Dornick Hills-Springer sand reservoir which are unusual in mid-continent operations. The study was undertaken in an attempt to define the producing mechanism or mechanisms that will control reservoir performance, as an aid in determining well completion and production practices.

GEOLOGY

The reservoir under consideration is a series of sand bodies of Pennsylvanian age found in the Lower Dornick Hills and/or Springer formations. For the purpose of this paper, the sand series is referred to as the Dornick Hills-Springer sand.

This sand series lies on the northeast flank of the Velma anticline, and dips very sharply to the northeast in TWP 1S-5W, the average dip being about 45°. However, as shown in Fig. 1, the trend of the pool swings eastward in TWP 1S-4W with a coincident decrease in dip angle. In this portion of the pool the average dip is about 25°. Faults in Sections 30-1S-4W and 32-1S-4W are shown in Fig. 1. These faults show only minor displacements for the horizon contoured in Fig. 1, but they do show a pronounced displacement of the immediately overlying beds. Similar faults are thought to exist in TWP 1S-5W; however, since the detailed geological studies necessary to properly define these faults were not available to the author, no attempt to show them in Fig. 1 has been made.

The up-dip productive limit throughout the pool is determined by the truncation of the Lower Dornick Hills-Springer sand. The down-dip productive limit does not appear to be defined by edge water, but by a gradual reduction in permeability of the sands. No dry hole has produced a significant volume of water from this sand section. There was a small gas cap in TWP 1S-5W.

Most of the wells in TWP 1S-5W encountered an oil sand 70 ft to 150 ft thick, a shale 20 ft to 80 ft thick, and another oil sand 50 ft to 130 ft thick. A few scattered wells in this area encountered other sand bodies below these

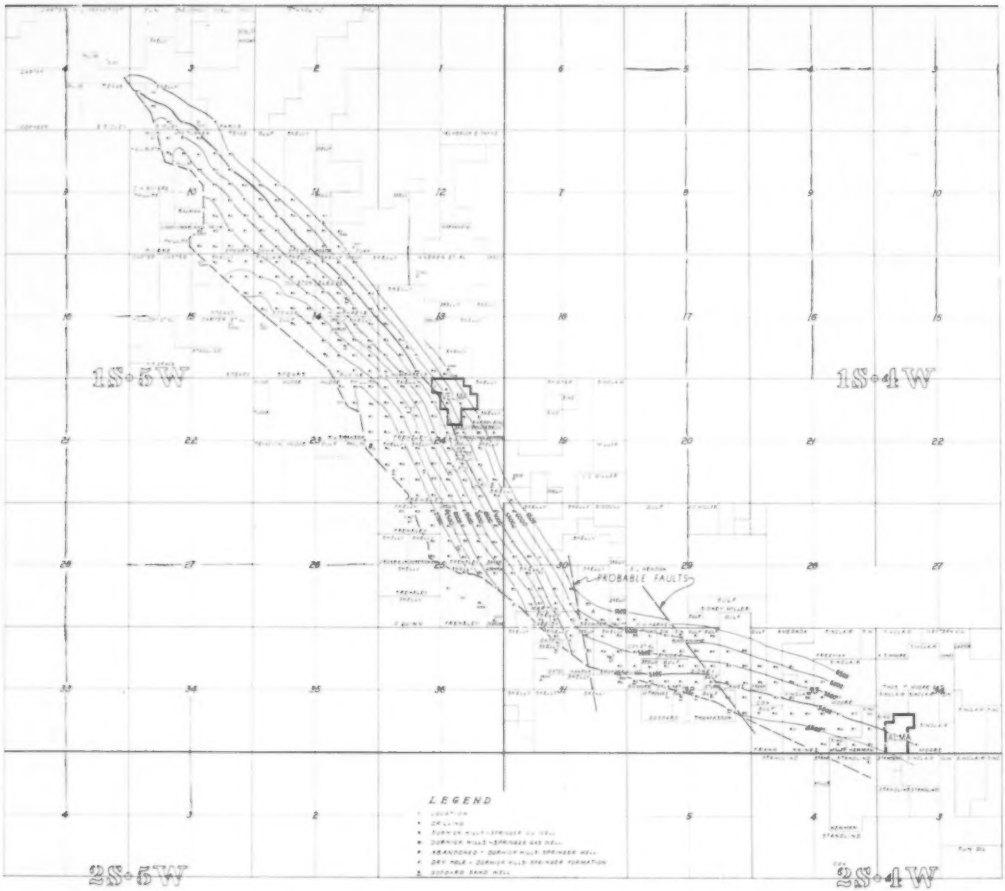

FIG. 1 — STRUCTURAL CONTOUR MAP OF TOP OF 1ST DORNICK HILLS - SPRINGER SAND. CONTOUR INTERVAL — 500 FT.

two varying from 10 ft to 495 ft thick. These lower sands do not always produce. Most of the wells east of the fault in Section 30-1S-4W penetrated only the first sand. A thin sand found below the first sand, usually referred to as the Goddard sand, produces in several wells near the up-dip productive limit of the first sand in TWP 1S-4W. Goddard sand wells are indicated in Fig. 1. Fig. 2 is a cross section based on electric log data showing sand conditions typical of the main body of the pool.

HISTORY OF DEVELOPMENT

Prior to the last quarter of 1944, most of the oil production in the Velma Pool was from various sand stringers in the Redbeds, Hoxbar, and Deese formations. In November, 1944, Skelly completed Frensley "F" No. 1 in Section 24-1S-5W in the Dornick Hills-Springer sand section. The well initially pumped about 15 bbl of oil per hour and no water. Only one additional well was completed in 1945. About 30 wells were completed in 1946, and de-

velopment averaged about 70 wells per year during 1947, 1948 and 1949. As of June 30, 1950, 274 oil wells and six gas wells had been completed. The pool is well defined and almost fully developed except for the southeast end. This development is shown graphically in Fig. 3.

Fig. 3 also depicts a history of the top allowables and total oil producing rate for the reservoir considered. In April, 1949, the Oklahoma Corporation Commission issued an order placing a limiting gas-oil ratio of 2,000 cu ft per bbl on all Pennsylvanian production in the Velma Pool. The order also fixed gas well allowables at a volume that would void as much reservoir space as an oil well producing at the limiting ratio. The June, 1950, gas well allowable averages about 200 Mcf/day/well. As a result of the February, 1950, gas-oil ratio survey, two oil wells were penalized for excessive ratios. In several cases, wells penalized for excessive gas-oil ratio have been worked over and the ratio reduced by cementing off per-

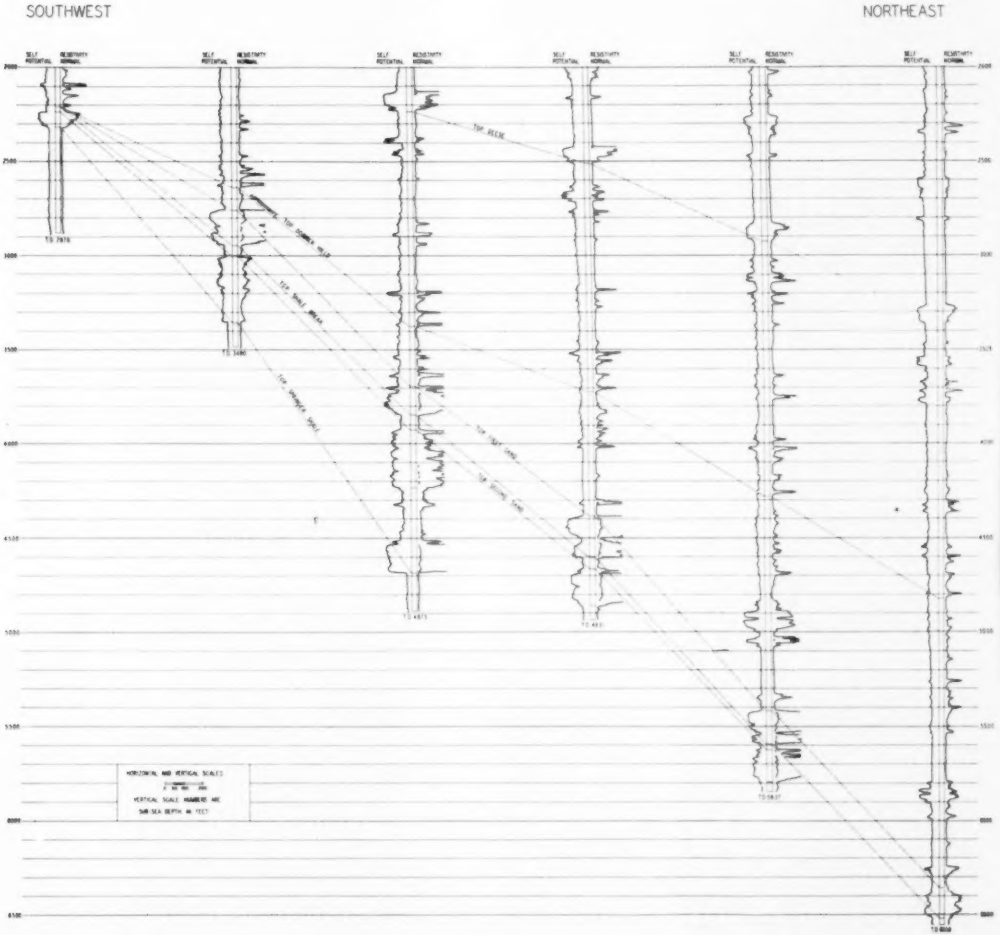

FIG. 2 — NORTHEAST - SOUTHWEST CROSS SECTION OF THE DORNICK HILLS - SPRINGER SAND, VELMA POOL.

forations or cementing a liner and perforating the lower portion of the section previously exposed.

In earlier wells, the usual completion practice was to drill a rotary hole through the pay section, run an electric log, set 7-in. OD casing through the producing section, and perforate opposite those intervals indicated to be sand on the electric log. More recent completion practice in TWP 1S-5W has been to set casing on the top of the second sand and perforate the first sand, or to set casing on the top of the first sand and use an uncemented slotted liner. In TWP 1S-4W, casing is usually set on the top of the one oil sand; however, some operators have used perforated completions in structurally high wells to facilitate the gas-oil ratio control which will be needed should gravity segregation occur to an appreciable extent.

Some wells flowed initially, but most of them pumped from 200 to 500 B/D of 28° API gravity oil. In very few cases did the reported initial production represent the capacity of the well. Producing BHP tests indicated that many wells were capable of producing 1,000-3,000 B/D if pumped down. The February, 1950, survey indicated that 29 wells were incapable of producing the February allowable of 80 B/D.

ROCK AND FLUID CHARACTERISTICS

The original reservoir pressure was 1670 psig at a datum of −4500 ft subsea. Since the average surface elevation is about 1100 ft, the original reservoir pressure was about 700 psi under the hydrostatic gradient. The average vertical gradient in the oil reservoir is 0.36 psi/ft.

Fig. 4 shows typical results of the analysis of a bottom-hole sample. Other than the relatively high viscosity, the sample characteristics are not unusual for a 29° API gravity oil. Since there was a small primary gas cap, the oil should have been saturated at the gas-oil contact (about −2400 ft subsea). Results of bottom-hole sample analyses taken at various structural elevations indicate that the oil at a given depth level in the reservoir was originally saturated at the BHP of that depth. Thus, for a given gravity of oil, the solution gas tends to increase at structurally lower positions.

Table I

Well	Subsea Top 1st Sand	Gross Ft of Section	Net Ft Oil Pay	Avg. Perm. Md	Avg. Poros. %	Est. Connate Water %
A	−3722	335	238	300	21	17
B	−4022	315	194	190	19	—
C	−4871	334	212	70	16	—
D	−5398	292	172	40	14	24
E	−5892	302	65	31	12	24

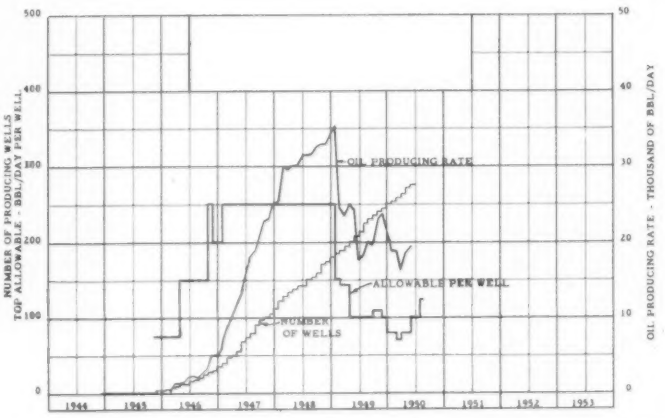

FIG. 3 — DEVELOPMENT AND PRODUCING RATES DORNICK HILLS - SPRINGER SAND RESERVOIR, VELMA POOL, STEPHENS COUNTY, OKLAHOMA.

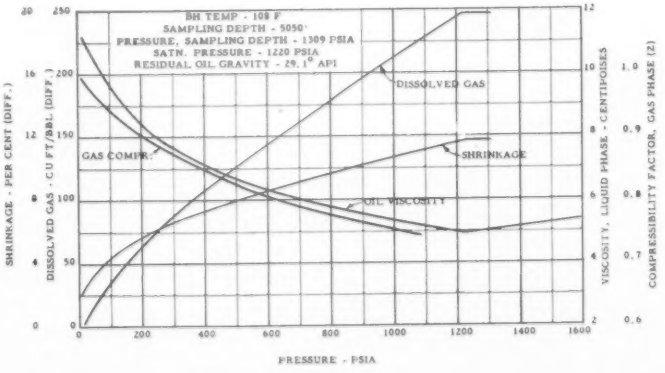
BH TEMP - 108 F
SAMPLING DEPTH - 5050'
PRESSURE, SAMPLING DEPTH - 1309 PSIA
SATN. PRESSURE - 1220 PSIA
RESIDUAL OIL GRAVITY - 29.1° API
DISSOLVED GAS
GAS COMPR.
SHRINKAGE
OIL VISCOSITY
SHRINKAGE - PER CENT (DIFF.)
DISSOLVED GAS - CU FT/BBL (DIFF.)
VISCOSITY, LIQUID PHASE - CENTIPOISES
COMPRESSIBILITY FACTOR, GAS PHASE (Z)
PRESSURE - PSIA

FIG. 4 — TYPICAL BOTTOM-HOLE SAMPLE ANALYSIS DORNICK HILLS - SPRINGER SAND.

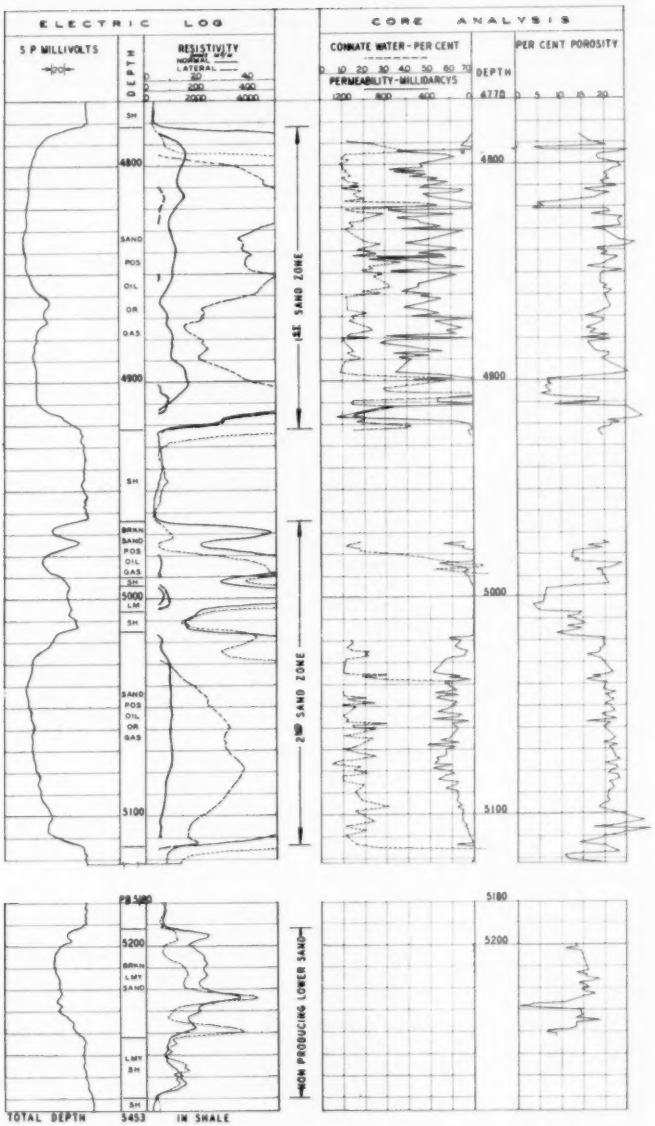

FIG. 5 — GRAPHIC WELL LOG OF TYPICAL WELL IN TWP 13-5W.

The stock tank oil gravity is fairly constant from the top of the productive closure down to about −5500 ft subsea, and averages about 28° API. In the south end of the pool, the stock tank oil gravity appears to vary approximately with structural position, decreasing down-dip. Fig. 6 is a portion of the structural contour map, on which have been superposed contours depicting the variation of stock tank oil gravity. It is likely that solution gas decreases with decreasing stock tank oil gravity. The fact that most of the wells producing lower gravity oil initially had lower gas-oil ratios tends to confirm this hypothesis.

The Dornick Hills-Springer sand is generally a fine-grained sand containing varying amounts of argillaceous material. In some places it has good permeability parallel to the bedding planes, but because of numerous paper-thin shale partings, permeability normal to the bedding planes is poor. In other places it is very clean sand. The average porosity and average permeability of the section have been found to be relatively uniform at wells of the same structural position but in different areas; however, the porosity and permeability of the sand appear to vary with structural position. This variation is illustrated in Table I by the core data on several wells in the same area. Similar variations in sand character occur in other parts of the reservoir.

The permeability of the sand penetrated by a given well is relatively uniform, and when core analysis results of several wells were arranged in order of increasing permeability, the data for each well were found to have approximately an exponential distribution[1] with r, the ratio of maximum to minimum permeability, varying from 15 to 35. The permeability to oil with connate water in place averaged about 50 per cent of the dry core air permeability on 70 samples tested.

Connate water saturations have been measured by the restored state method, by retorting samples of cores taken using oil base mud, and by the use of electric logs. The use of electric logs to calculate connate water has not been entirely satisfactory because the resistivity of the formation water must be known and no well has produced enough water to make it certain that a sample taken was uncontaminated Dornick Hills-Springer sand water. Restored state method results and oil base core results agree very well, usually within 1 per cent saturation; however, electric log calculations usually give values lower than those obtained by the

other two methods. The average connate water saturation for the reservoir is estimated at 20 per cent of the pore volume.

Fig. 5 is a graphic well log showing the electric log and core data of a typical well in the main body of the pool. This well had both the first and second sands well developed. It also penetrated a poorly developed, nonproductive third sand. Because of the 45° dip, the actual thickness of these sands measured normal to the bedding planes is only about 70 per cent of that shown on the electric log. For the same reason, the average area drained by a well on 10-acre spacing is about 14 acres. Thus, the electric log thickness multiplied by the spacing may be used to calculate sand volumes.

Results of the analysis of about 3500 ft of core indicate that the average porosity of the oil sand is 18 per cent, the average permeability is 150 md, and the average connate water saturation is 20 per cent. Using these figures and an average formation volume factor of 1.19, the average original stock tank oil in place may be calculated to be 940 bbl per acre ft. In TWP 1S-5W, the first sand averages 108 ft of net pay, and the second sand 91 ft of net pay.* Thus, the original stock tank oil in place averages 187,000 bbl per acre, exclusive of any productive lower sands. In TWP 1S-4W, the first sand averages 113 ft of net pay, making 106,000 bbl per acre average original stock tank oil in place. The presently developed portion of the reservoir is estimated to have originally contained 430 million bbl of stock tank oil in the first and second sands.

RESERVOIR PERFORMANCE

Since this reservoir is, for practical considerations, a closed stratigraphic trap, there is no reason to expect an effective water drive. Past performance has shown no evidence of a significant volume of water influx. A few wells have made very small volumes of water, and in no case has the water producing rate increased.

With a gas saturated crude and such steep dips, it would be anticipated that the effective producing mechanisms would be a dissolved gas drive and gravity drainage. The performance to date tends to support this hypothesis.

Fig. 7 shows some performance data for the reservoir. The BHP curve is labeled "approximate," because it was necessary to correct some pressure measurements 2000 ft below TD and to correct others 2000 ft up into the casing in order to base them all on a common datum. The reservoir has produced about 29,000,000 bbl as of June 1, 1950, an average of 59,000 bbl/psi drop.

The only points shown on the GOR curve are the initial average solution GOR and the August, 1949, and February, 1950, surveys. The latter two points are numerical averages of the ratios of all wells in this reservoir. The accuracy of these numerical averages was checked for a few leases by comparing the numerical average of the survey ratios with weighted average ratios (all gas metered). Generally, they differed by less than 15 per cent. The decrease

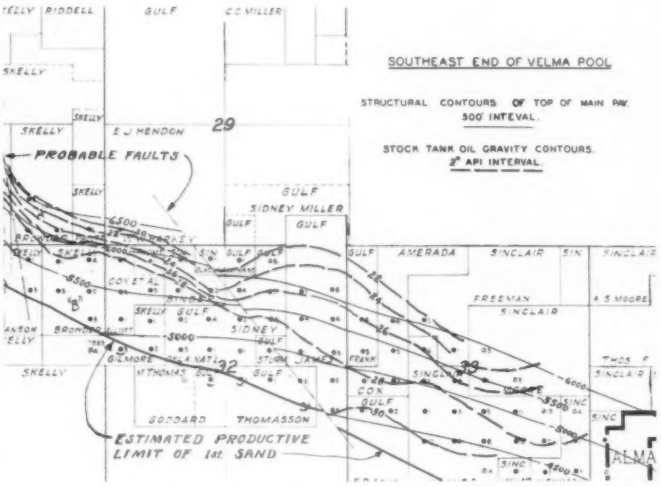

FIG. 6 — SOUTHEAST END OF VELMA POOL.

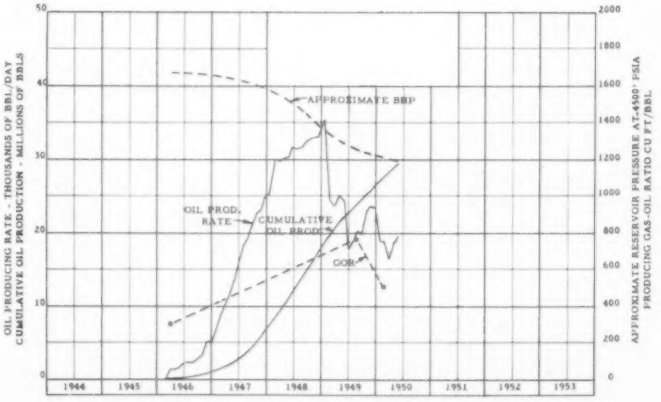

FIG. 7 — DORNICK HILLS-SPRINGER SAND, VELMA POOL PERFORMANCE DATA.

*These figures are measured vertically rather than normal to the bedding planes, since oil in place per acre is usually based on surface acres.

in GOR from August, 1949, to February, 1950, is accounted for partially by the fact that some very high GOR wells were successfully worked over, and partially by a general decrease in ratios. Such an occurrence is not common to solution gas drive performance, and is thought to be indicative of gravity drainage effects.

Because there is considerable doubt as to whether the bottom-hole pressure data are representative of reservoir conditions, no attempt has been made to calculate oil initially in place by the use of material balance equations. For the same reason, no attempt has been made to verify or deny by material balance methods the hypothesis that there has been no water influx.

It is apparent that average reservoir performance data are not conclusive as to producing mechanism. In an attempt to find some more definitive data, the performance of several individual wells was examined. Fig. 8 is typical of the performance data of the older wells in the pool. The dissolved gas drive performance was calculated by the method introduced by Muskat,[2] using bottom-hole sample data similar to those shown in Fig. 4. The slope and position of the straight line portion of the K_g/K_o curve used was an average of the field data for some sands of similar texture, and the equilibrium gas saturation was estimated at 9 per cent of the pore volume from some performance data of several early wells in the Dornick Hills-Springer sand that were produced at high enough rates that gravity drainage effects were thought to be small. The basic differential equation describing the pressure history was integrated by the Runge-Kutta method.[3] Because the sand in this area is laminated with paper-thin shale partings, the calculated performance curves were corrected for permeability stratification by the method described by Keller, Tracy and Roe.[4] This method assumes no vertical permeability, and consequently results in some large pressure differentials across shale partings, but it is believed to constitute some improvement over the assumption of an isotropic reservoir. It is apparent that the well performance was following the calculated solution gas drive performance fairly well until cumulative oil recovery reached 5½ per cent of the pore volume. Then the allowable was curtailed sharply, and instead of continuing to rise, the GOR decreased, and at the time of the latest test data shown, the GOR was considerably less than the ratio calculated assuming solution gas drive. This phenomenon also was observed in other wells, and it is believed indicative of some resaturation of the sand around this well by gravity drainage.

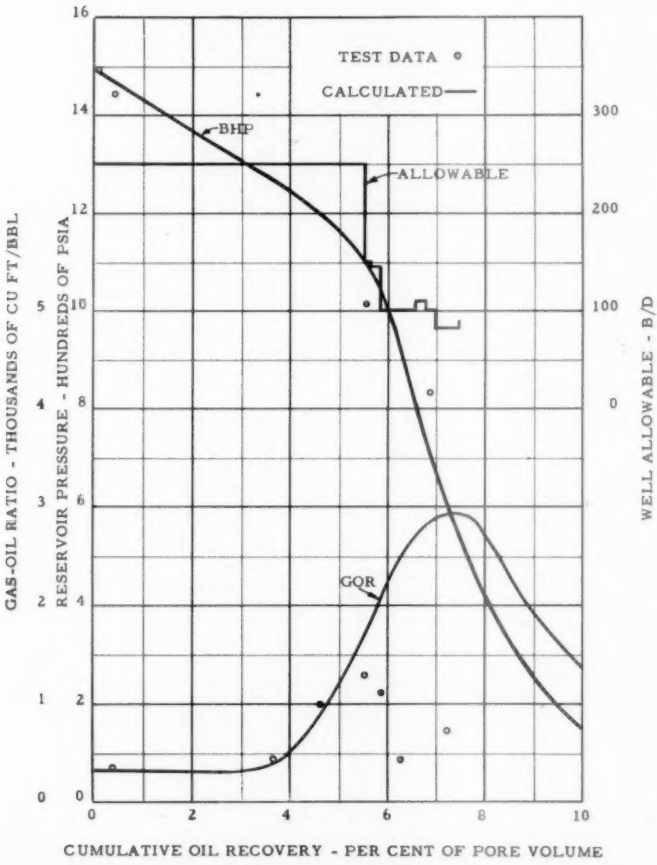

FIG. 8 — DORNICK HILLS - SPRINGER SAND, VELMA POOL. COMPARISON OF ACTUAL PERFORMANCE OF A WELL WITH CALCULATED DISSOLVED GAS DRIVE PERFORMANCE.

It appears solution gas drive has been the principal producing mechanism in this reservoir in the past; however, there is some evidence of the effects of gravity. Probably gravity drainage will play an increasingly important role in the operation of this reservoir as it is further depleted. It does not appear likely that all the gravity drainage oil will be recovered at the structurally low wells as has been the case in some gravity drainage reservoirs, because the decreasing permeability down-dip will cause the oil to drain downward at successively decreasing rates, and this should tend to partially resaturate the sand around wells of intermediate structural positions, causing them to recover some additional oil. In those areas where the sand is laminated by paper-thin

shale partings, the rate of gravity drainage will be restricted because the oil will be denied a vertical path and forced to follow the dip angle. If there is an appreciable tendency for the shale partings to divide the sand into closed lenses, considerable oil may be trapped, and the gravity drainage recovery seriously reduced.

The estimated ultimate oil recovery by solution gas drive alone would be 18 per cent of the original stock tank oil in place. The additional oil to be expected because of the effects of gravity cannot be predicted very accurately. Some experiments have indicated that sand samples with permeabilities of 300-1000 md will drain down to as low as 10 per cent residual oil saturation; however, it is unlikely that less permeable samples would reach such a low saturation. If the oil at saturations below 30 per cent is considered immobile, and it is assumed that the gas drive recovery plus an additional 50 per cent of the mobile oil can be recovered, the ultimate recovery will amount to about 37 per cent of the original stock tank oil in place. Probably much of the gravity drainage oil will be produced at relatively low rates over a long life.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of the members of the Production Engineering Section, Tulsa Division, Gulf Oil Corp., in making this study, particularly A. C. Godbold for his advice, and Marion Smith and George Girouard for assembling and interpreting data. The section entitled "Geology" was prepared under the guidance of the Geological Department, Tulsa Division, Gulf Oil Corp., and the geological data shown are the results of studies by members of that department. The author wishes to thank the management of the Gulf Oil Corp. for permission to publish this paper.

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3. Sherwood and Reed: *Applied Mathematics in Chemical Engineering*, McGraw-Hill, (1939), 122.
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The Drift of Things

. . . as followed by **EDWARD H. ROBIE**
Secretary AIME

DEMAND and supply of engineers, present and future, has had more than the usual amount of attention in the last year. Since the end of the last World War new peaks have been attained in engineering enrollments in the colleges. The subject seemed to be particularly attractive to the GI's who took advantage of the Government's offer to finance their education. In the prewar decade some 11,000 engineers had been graduated annually. The figure rose to 19,000 in the academic year 1946-47, to 31,000 in 1947-48, to 47,000 in 1948-49, and to 51,000 in 1949-50. This for a time saturated the market, and those graduating last June, for the first time in years, found a buyer's market.

A year or more ago the Department of Labor came out with a flat statement that "the number of graduates will greatly exceed the number of engineering job openings in the next few years." This was based on a study that indicated that "the number of graduates needed would approximate 17,000 or 18,000 annually for the next several years." Contrasted with this, it was estimated that 36,000 would be graduated in 1951 and 29,000 in 1952. Unfortunately this pessimistic statement received wide publicity and discouraged many young men from entering engineering. Difficulties reported in securing jobs six months ago added to their feeling that perhaps for the next few years engineering was a poor field to enter. Freshmen engineering enrollment currently is only about 27,000. Instead of more than 5 per cent of high school graduates going into engineering, as was true in 1947, this year only 2.2 per cent selected this field.

Selective Service has indicated that the upper half of the current 27,000 students will be deferred to continue their education next year, or 13,500. Those in the upper two-thirds of the sophomore class, or 9,000, could continue as juniors; and the upper three-quarters of the juniors, or perhaps some 7,000, could graduate in 1954. Against this, Dean Hollister, of Cornell, believes 20,000 engineering graduates will be needed annually for peacetime needs alone, and that the present emergency will increase this number, for both civilian and military needs, to 30,000.

Even if Selective Service were not withdrawing any engineering students at all, Dean Hollister estimates the number of graduates in 1951 at 32,500; in 1952 at 21,900; in 1953 at 17,000; and in 1954 at 12,400.

It is plain that the top half of high school students, particularly those who rank high in mathematics, science, and may we add English, should be apprised of the excellent opportunities that seem almost certain to be open to engineering graduates in the next few years. AIME members can help to do this, and present engineering students can tell their younger brothers and their friends that this is a field of high promise.

Furthermore, those who feel no particular urge to go out and shoot somebody, and have the intellect to stay in the top half of their class at an engineering college, have some assurance, at least, that they will be allowed to serve their country in a more constructive way than by carrying a gun. Engineers Joint Council, of which the AIME is a component society, is doing everything possible, through its Engineering Manpower Commission, to see that an adequate flow of engineers shall come out of our schools in the future years, and that their talents are thereafter used to the best advantage.

The Personnel Service

No matter how easy it is for an engineer to find a job in times like these, most AIME members are faced, at one time or another, with the necessity of looking for one. Here is where the Engineering Societies Personnel Service can be helpful. It is a nonprofit corporation set up by the Founder Societies and the Western Society of Engineers to act as a clearing house for engineering jobs. Right now it has far more opportunities than it has men to fill them. Often it has openings for men in the higher salaried brackets. It costs nothing to register with the Personnel Service, and if a job is thereby secured the fee is considerably less than would be charged by a commercial service. So if you need a job, or want a better one, as who doesn't, it may well pay to register. Offices are maintained at 8 W. 40th St., New York 18, N. Y.; 100 Farnsworth Ave., Detroit; 84 E. Randolph St., Chicago 1; and 57 Post St., San Francisco.

Employers, too, should register their needs, for which there is no charge.

Book Manuscripts Wanted

Twenty years ago the family of the late Seeley W. Mudd contributed $100,000 to the AIME, establishing a fund whose income was to be used "for the advancement of the sciences of mining and metallurgy by the encouragement of research and the dissemination of knowledge, and for the promotion of the welfare of engineers engaged in the professions of mining and metallurgy." A further suggestion was that preference be given to projects of particular benefit to young engineers. Accumulated unspent income in the Fund now totals some $36,000. A part of the income has heretofore been used to publish or purchase books subsequently given free of charge to new Junior Members of the Institute. Money in the Fund has also been used to underwrite preparation and publication of such books as *Industrial Minerals and Rocks*, *Elements of the Petroleum Industry*, *Coal Preparation*, *Basic Open Hearth Steelmaking*, and Biringuccio's *Pirotechnia*.

The Committee administering the Fund is now seeking material for new volumes, either for free distribution to Junior Members, or in the latter category, for general sale. If any member of the AIME has the material for a good book in his system, or knows of some one who has; or if he can suggest a topic and an author for a book that will fill a gap in the literature; then we should like to be advised.

Identify Yourself

One way that AIME members can assist Institute headquarters, and at the same time perhaps serve themselves, is to add "Member AIME" to their signature when signing a letter. We try to give the best and quickest possible service to everybody, but members naturally get the preference. Also, they get discounts on most of their orders, so the correspondence of nonmembers must be segregated. It is likewise filed separately.

H. S. Rogers Reelected Chairman of ECPD

Engineers Council for Professional Development held one of its best attended and most successful annual meetings in Cleveland recently, with a registered attendance of 174. Harry S. Rogers, president of the Polytechnic Institute of Brooklyn, was re-elected chairman of the Council, and L. F. Grant, field secretary of the Engineering Institute of Canada, vice-chairman. William N. Carey succeeds C. E. Davies as secretary, with Edward H. Robie as assistant secretary. C. E. Lawall, Curtis L. Wilson and James R. Cudworth are the official AIME representatives on the Council. All were present at the Cleveland meeting, as were W. R. Chedsey, James L. Head, D. R. McKeithan, and L. E. Young, of the AIME.

The Committee on Student Selection and Guidance becomes the Guidance Committee, with W. F. Thompson as chairman; the Committee on Engineering Schools becomes the Education Committee, with S. C. Hollister continuing as chairman; the Committee on Professional Training becomes the Training Committee, with A. C. Monteith remaining chairman; the Committee on Professional Recognition becomes the Recognition Committee, R. H. Barclay continuing as chairman; the Committee on Engineering Ethics becomes the Ethics Committee, with William F. Ryan as chairman; the Information Committee continues, with Walter E. Jessup as chairman; and a new Student Development Committee has been set up, to coordinate and administer relations between the engineering schools, the engineering societies, and industry, for the purpose of promoting the professional development of engineering students except as assumed by the Education Committee.

In the mineral industry field, the following curricula were reported as having been accredited for the first time in 1950: Geological Engineering, at Arizona, Idaho, Minnesota, Pittsburgh, and South Dakota School of Mines. Mining Engineering, geology option: Missouri School of Mines. Metallurgical Engineering: Arizona and Wayne. Petroleum Engineering (petroleum and natural gas): Texas College of Arts and Industries.

Among the most important reports presented at the meeting was that by the Committee on Training, of which Mr. Monteith is chairman, summarizing a two-year study on the first five years of professional development. The report was in six parts, discussing (1) orientation and training of the young engineer in industry; (2) the continued education of graduate engineers; (3) integrating the young engineer into his community; (4) registration of the young engineer; (5) self-appraisal methods for valuable characteristics in engineering; and (6) reading list and selected bibliographies.

A new record was made by ECPD in the prompt printing and distribution of its annual report, of 53 pages. This report, which contains among other things a complete list of accredited curricula in engineering schools and technical institutes, is available for 50 cents from the Secretary of ECPD, 29 W. 39th St., New York 18, N. Y., stamps acceptable.

ECPD is a joint organization sponsored by the four Founder Engineering Societies, plus the Engineering Institute of Canada, the American Society for Engineering Education, the AIChE, and the National Council of State Boards of Engineering Examiners, all of whom contributed $9,480 to its income in the current year. Cash on hand and in bank at the end of the fiscal year ended Sept. 30, 1950, was $21,958, compared with $13,796 a year before. Principal items of income aside from the $9,480 above noted were: fees for inspecting engineering schools, $19,243; sales of publications, $13,038; and grant from Engineering Foundation, $5,000. Principal items of expense were: inspections of curricula, $21,559 (including $948 overhead); publications, $6,098; and salary, $4,000. Total income was $47,472; total expense, $39,310. Comparable figures for the previous year were $37,722 and $36,535, respectively. ★ ★ ★

AIME's Mexico Section Will Welcome Visitors

Luncheon meetings of the newly organized Mexico Section of the AIME are held on the first Monday of each month at the American Club in Mexico City. AIME members who may be in the city at that time will be welcomed. They should get in touch with William G. Kane, secretary-treasurer of the new Section, whose post office address is Apartado 711, Mexico, D. F., and whose street address is San Juan de Letran No. 9, Desp. 805; telephone 10-27-24.

Officers of the new Mexico Section are: chairman, Alfredo Terrazas; vice-chairman, Valentin Garfias; secretary-treasurer, William G. Kane. ★ ★ ★

Board Alters Policy For Student Associates

Several actions were taken by the AIME Board of Directors at its meeting that affect Student Associates. Instead of continuing Student Associates on the rolls after they become in arrears for dues they will be dropped at the end of three months after their dues become available. Thus they can apply for reinstatement and change of membership grade at any time in the future without being penalized for any arrears in dues that may have been incurred. Where such arrears have been debited against a Student Associate in the past, the sum of $1 is to be charged for reinstatement, regardless of the amount of accumulated arrears. Student Associates are also exempted from any registration fee at the forthcoming Annual Meeting in St. Louis, though they will receive the same technical papers as are distributed to those who pay the $5 or $8 registration fee. Students who are not Student Associates of the Institute will pay a registration fee of $1. ★ ★ ★

Three More Awards Recommended By Board

In addition to the Awards to be made at the forthcoming Annual Banquet that have already been announced, the Board of Directors, AIME, at its Nov. 15 meeting, approved the following recommendations:

J. E. Johnson, Jr., Award: to Samuel Naismith, evaluation engineer, Oliver Iron Mining Co., Duluth, "for his contribution to the development of the utilization of low-grade Lake Superior iron ores for blast-furnace use."

Robert W. Hunt Award: to R. R. Webster, research engineer, and H. T. Clark, manager of metallurgical research, Jones & Laughlin Steel Corp., Pittsburgh, for their paper, "Side-Blow Converter Process for the Production of Low-Nitrogen Steel Ingots," published in the JOURNAL OF METALS for May, 1950. The Award is to consist of a certificate and silver medal to each author, and a $250 prize to Webster, the only author under 40 years of age.

Robert H. Richards Award: to Frank R. Milliken, assistant manager, Titanium Division, National Lead Co., New York City.

Announcement was also made that the Alfred Noble Prize this year goes to Ralph J. Kochenburger, a member of the AIEE. ★ ★ ★

PROPOSED FOR MEMBERSHIP

Total AIME membership on September 30, 1950, was 16,737; in addition, 4,184 Student Associates were enrolled.

ADMISSIONS COMMITTEE

A. J. Phillips, Chairman; George B. Corless, John T. Sherman, Lloyd C. Gibson, R. D. Mollison, Plato Malozemoff, Ivan Given. Alternates, H. P. Croft, F. W. Hanson, T. D. Jones, Frank A. Ayer, H. W. Hitzrot, H. K. Masters.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend its privileges to every person to whom it can be of service but does not desire to admit persons unless they are qualified.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; AM, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

CALIFORNIA

Fullerton — Stoner, Robert A. (J).
La Habra — Yaplee, Harry S. (J).
Los Angeles — Baker, Weldon M. (J).
Palos Verdes Estates — Tizard, William E. (M).
San Francisco — Elliott, Myron R. (J) (C/S-S-J).
Taft — Sacre, Leverett P. (M).

COLORADO

Durango — Brinker, Tyler (J) (C/S-S-J).
Rangely — Freehling, Robert N. (M).
Yuma — Bronte, Robert F. (J) (C/S-S-J).

ILLINOIS

Flora — Mitchell, Robert W. (M).

KANSAS

Manhattan — Yee, Bing Q. (J) (C/S-S-J).

LOUISIANA

Crowley — Murray, Edward E. (J).
New Orleans — Capps, Charles A. (A); Dupre, Harry (M) (C/S-J-M); Helm, Malcolm B. (M).
Shreveport — Cobb, Joseph B. (M).

MISSISSIPPI

Natchez — Gauthier, Anatole C., Jr. (J) (C/S-S-J).

NEW YORK

Scarsdale — Berlin, Edson W. (M) (R-M).

OKLAHOMA

Drumright — Bellinger, Norman (J) (C/S-S-J).
Ponca City — Rummell, Willis B. (J).
Tulsa — Bodemann, Louis C., Jr. (J); Corbitt, James P. (J) (C/S-S-J); Girouard, George E., Jr. (J); McCann, Burton E. (M); Redmond, John F. (M) (R); Rodrigues, Oscar G. (J); Smith, Marion R. (J).

OREGON

Portland — Brugman, Francis W. (A).

SOUTH DAKOTA

Rapid City — Ryan, John M. (A).

TEXAS

Bay City — Mills, Edgar N. (J) (C/S-S-J).
Beaumont — Brooks, Glen D. (J) (C/S-S-J).
College Station — Cretsinger, James H. (J) (C/S-S-J).
Dallas — Elliott, William D. (J) (C/S-S-J); Reudekhuber, Frank O. (J).
Fort Worth — Clay, James A., Jr. (M) (C/S-J-M); Gillespie, Clarke B. (J) (C/S-S-J); Winston, Harold S. (J) (C/S-S-J).
Houston — Angevine, Robert H. (J) (C/S-S-J); Black, William M. (J); Simpson, Jay P. (J); ten Brink, Karl C. (M).
Kingsville — Gilstrap, Tommy O. (J).
Midland — Bundrant, Charles O. (M); Morgenthaler, Charles E. (J) (C/S-S-J); Sherrod, Gerald E. (J).
Monahans — Teel, James R. (J) (C/S-S-J).
Roma — Guerra, Arturo (J) (C/S-S-J).
Waco — Walsh, Alva G. (J) (C/S-S-J).
Greenriver — Manuel, Tom (J) (C/S-S-J).

WYOMING

Casper — Nelson, David R. (J); Towne, Donald F. (J) (C/S-S-J).

CANADA

Alberta — White, Ronald J. (J) (C/S-S-J).

VENEZUELA

Caracas — Loeb, Otto (A).
Caripito — Debs, Salim G. (J).
Zulia — Moreno, Peter J. A. (J) (C/S-S-J).

★ ★ ★

Gold Standard

Continued from Page 19, Section 1

stable economy if we do a better job of balancing our imports and exports. We should alter our stockpiling method to include more than just enough strategic materials for immediate purposes. While it is true that this country is not as yet a "have not" nation, and it is not likely to become such a nation in the near future, nevertheless, certain of our basic natural resources once held in abundance will some day be depleted. It was suggested that instead of exporting our materials today taking credit notes for the purchase price, that we begin stockpiling from imports of such metals as chrome, mercury, tungsten, manganese, copper and zinc.

Following President McLaughlin's talk, the group was shown a movie entitled "Limestone Pore Space Studies" which was filmed and presented by the Stanolind Oil and Gas Co. ★ ★ ★

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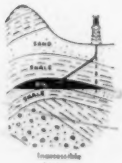
Eastman Directional Drilling was first used to explore productive zones off the California Coast by drilling wells from shore to subsea formations. Since that time many new applications of DIRECTIONAL DRILLING have been made by competent Eastman engineers to the extent that Directional Drilling now is utilized extensively and applied successfully in the following manner: EXPLORING geological structures by drilling multiple wells from single locations; EXPLOITING new oil reservoirs; DEFLECTING the course of the well to reach otherwise inaccessible bottom locations; SIDETRACKING obstructions and STRAIGHTENING the hole; REDRILLING old wells profitably; and CONTROLLING wild wells.



Eastman engineers prepare carefully planned proposals in advance of the actual directional drilling work that is to be undertaken by the operator. These engineering suggestions are based upon vast experience in all major oil fields.

Accurate completion reports are compiled for the operator after the work is finished. These records, showing methods, techniques, and specialized tools used, serve as a reference to make future directional drilling operations more economical.

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AIME Officials for 1951 To Take Office Feb. 20

Officers and new Directors of the AIME for 1951, to take office at the annual business meeting, Tuesday, Feb. 20, were declared duly elected at the Board meeting on Nov. 15. No candidates in opposition to those named by the Nominating Committee were offered. The new officers and Directors for 1951 thus are (as published in the July journals): W. M. Peirce, President; Joseph L. Gillson and Michael L. Haider, Vice-Presidents; Thomas G. Moore, Charles E. Lawall, John F. Myers, Fay W. Libbey, A. C. Rubel and Leo F. Reinartz, Directors. The following Division Chairmen are Directors ex officio: Carroll A. Garner, A. B. Cummins, R. M. Brick, T. L. Joseph, Richard J. Lund, Allison Butts, Raymond E. Byler, Oliver C. Ralston, Richard W. French, Jr., and the Chairman of the Mining, Geology, and Geophysics Division who remains to be elected. ★ ★ ★

Jr. Members Must Change Status at Age 33

Junior Members of the Institute reaching the age of 33 are now required to change their status to Associate Member or Member. They are automatically elected to Associate Membership unless they apply for the higher professional grade, which requires six years of experience in the mineral industry, three years of which must be in positions of responsibility. To make transition as easy as possible in view of the requirement that an initiation fee be paid by either Associate Members or Members, the Board of Directors at its Nov. 15 meeting voted that the initiation fee for Junior Members so transferring be billed in four annual installments of $5 each. If such Junior Members are in arrears for dues, they may also pay such arrears in four annual installments. ★ ★ ★

Three Engineers Named By Truman for NSFB

Through the efforts of Engineers Joint Council, three engineers have been appointed by President Truman to serve on the National Science Foundation Board. They are D. H. McLaughlin, Andrey A. Potter and Edward L. Moreland. Originally no engineers had been considered for membership on the Board but EJC pointed out the advisability of having the profession represented and offered a list of qualified men, three of whom were selected for the 24-man Board. A committee of EJC will continue its Science Legislation Panel to maintain active contact with the three engineers on NSFB and give them any support that may seem desirable.

Among other things discussed by Engineers Joint Council at its meeting on Nov. 17 was the progress of the Engineering Manpower Commission. This group has been set up to do all that is possible to see that engineers are used to the best advantage in the present emergency, and also to see that a continuing supply of engineers is provided by the colleges in the years to come. The Commission was to complete its recommendations early in December and present a united front, with the National Research Council, the American Chemical Society, and the American Institute of Physics, in presenting the case for engineers and scientists before the National Security Resources Board.

President of Engineers Joint Council for the coming year will be James M. Todd, past-president of the ASME, and C. E. Davies, secretary of ASME, will be EJC secretary. ★ ★ ★

Zay Jeffries Elected AIME Honorary Member

Zay Jeffries, a retired vice-president of the General Electric Co., Pittsfield, Mass., was, on Nov. 15, elected to Honorary Membership in the AIME. This small group is limited to 20 living members, and only 80 distinguished engineers and scientists have been so honored since the Institute was founded in 1871. With Jeffries' election, but one vacancy remains.

Jeffries has been prominent in the field of metallurgical research in the diverse fields of theoretical metallurgy, aluminum alloys, and powder metallurgy. He has been equally outstanding in the administration of industrial research and development. His professional and administrative talents and efforts have made major contributions to the development of the tungsten filament lamp industry, to the establishment of the sintered carbide casting tool, and to the development of new and improved industrial aluminum alloys.

He has long been a member, and a professionally active one, of the AIME, having contributed a host of professional papers to its volumes and participated actively in its metallurgical discussions for more than 30 years. He has been both the Institute of Metals Annual Lecturer (1924) and the Iron and Steel Division Howe Memorial Lecturer (1930), and was James Douglas Medalist in 1927. In 1936 he was awarded the John Fritz Medal, given by the four Founder Societies "for notable scientific or industrial achievement." ★ ★ ★

ASME Votes to Raise Dues to $25 Per Year

By a vote of at least two-thirds of the voting members, as provided by the bylaws, the American Society of Mechanical Engineers has voted to raise its dues by $5 effective October, 1951. The new rate is $25 per year for Fellows, Associates, Members, and Junior Members over 33 years of age; $20 for Junior Members 30 to 33; and $10 for Junior Members less than 30 years of age. ★ ★ ★

Correction

The sale price to AIME members of the Statistics of Oil and Gas Development and Production volume was incorrectly published as being $4.20 on Page 7, Section 2 of the November issue of the JOURNAL.

The price to members is $3.00 per copy. ★ ★ ★

Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 601 Continental Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to the position coded Y4244 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

PERSONNEL

♦ Petroleum Engineer, executive, 55, available about March 1, 1951, for domestic or foreign service. Thirty years' experience in all phases of oil and gas production, U. S. and foreign. Code 141.

POSITIONS

♦ Geologist for staff position in research laboratory, to act as geologist, sedimentologist in connection with oil field secondary recovery project. Location, western Pennsylvania. Y4244. ★

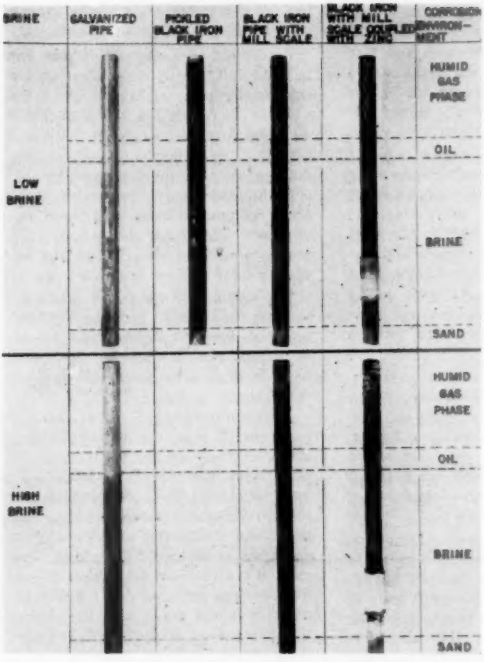

FIG. 4 — SIMULATED OIL WELL EXPERIMENT. CYCLE: SAMPLES WERE RAISED DURING THE NIGHT TWO INCHES TO SIMULATE THE CHANGING SOLUTION LEVELS IN AN ACTUAL WELL. AERATION: 5 PER CENT CO_2, 95 PER CENT AIR. TIME: TWO MONTHS. ROOM TEMPERATURE.

BATTELLE INSTITUTE

Continued from Page 13, Section 1

It is not unreasonable to believe that methylcyclopentene would behave like propylene in such a reaction. The esters may be used in considerable tonnage as solvents, pest repellents, and plasticizers.

BATTELLE has been of assistance, too, in the development of outlets for refinery by-products. Pan American Refining Corp. sponsored such work, with emphasis on dark-colored polymer from the catalytic refining of cracked gasoline. That polymer behaves like a drying oil, forming a hard, very brittle film in eight hours. Numerous laboratory formulations led to the selection of several which were similar in performance to commercially available freight car and aluminum paints, baking varnishes, alkyds, and linseed oil-base paints. More recently, the sponsor has produced a light colored material of similar properties which even further extends the applications of the company's products into the coatings market.

Additional descriptions of specific problems would tend to repeat some of the foregoing. Very briefly, here are a few others. Hydroformer polymer has been found, as was expected, to be effective as a wood preservative, in much the same way as creosote is. In addition, it serves as a vehicle for any of several copper compounds, giving a multipurpose preservative for marine exposure.

Research on aircraft hydraulic systems to reduce failures in service has involved studies of the interaction of rubber "O" rings and petroleum-base hydraulic fluid — absorption of the fluid by the rubber rings and extraction of plasticizer from the rubber by the fluid.

A comprehensive study has been made of the factors involved in the dust-proofing treatment of stoker-size coal with petroleum oils. Although numerous variables affect the final result, one of the most striking was the water content of the coal which, when high, enabled the oil to migrate inward away from the surface, where it does the most good. Such a coal lost its dustless qualities in storage fairly rapidly and required a comparatively high-viscosity oil.

A new project has recently been started for the Texas Eastern Transmission Co. to find ways of improving performance of pipes for the transmission of natural gas. Already, welding, process metallurgy, mechanical engineering, and physical metallurgy research divisions have joined forces to solve the problem.

It is hoped that this paper may serve the purpose of demonstrating how the independent, nonprofit research institute, of which Battelle is an example, has been and can be of service to the petroleum industry. To be able to employ such parts of a complete research organization as may be needed for a particular problem is important in these times of rapidly changing emphasis — when obsolescence may occur over an interval of three years, or even less. The research institutes stand ready, with expert personnel and the best of equipment, to do for industry the research that it needs. ★★

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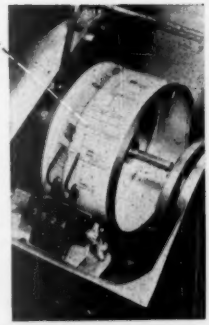

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TIME WILL TELL

THE GEOLOGRAPH CO. INC.

P. O. Box 1291 Oklahoma City 1, Okla.

Wartime Conditions

Continued from Page 18, Section 1

intentionally misdirected him. Trying to find your way around in wartime Washington can be the most frustrating experience of a lifetime.

Its something like trying to drive your car from Texas to some small town in New England if all the road maps, signs and highway number markers were suddenly wiped out. Imagine trying to get through St. Louis, Pittsburgh, or Cleveland, Newark, New York, Boston, with no highway markers, no signs, no maps.

Another big problem you will have to face is manpower. In my opinion — and that of a lot of men who know much more about it than I do — the manpower problem is going to be your biggest headache by an overwhelming margin.

We came out of the threadbare thirties and into the last war with a very large manpower surplus. We had millions of officially unemployed. We had other millions of boys and men on the farms whose work was not absolutely necessary to run the farm. But there were no jobs in town for them. We had a million or more young girls, on the farms, in the towns and cities, living at home and not officially unemployed because they had never had a regular job.

And yet, with all of this at the start, before the war was over, we were scraping the bottom of the manpower barrel. Do you remember just a few short years back when you talked about some of the boll weevils you had to hire?

I wouldn't argue with anyone who said that some of the sorriest sad sacks you now have on your payroll are going to look like manna from heaven to you within a couple of years.

What can you do about it? The first thing is to realize that Washington isn't going to solve all of your problems. Then you can use your head and sit down and do some plain common sense planning.

Again the first step is to get the facts. Take an inventory of your manpower situation. Then check the distribution of your men by age groups. Don't let yourself be caught with all young men in one district and all old men in another. You may wake up some day to find practically all of the young men gone into the armed services. Get your older men distributed right now if they are bunched. Don't let any of your older men retire if you can talk them out of it.

Start upgrading your men by special training programs. Start down grading jobs that call for a lot of skill and experience, by breaking up one complex job into several simpler jobs. You may think it a wild idea but right now I wouldn't bet money that a lot of you won't have at least a few women working on leases in less than three years.

You and I know that there is a big difference in the amount of heavy lifting, dragging, tugging, and heaving equipment around on an average oil lease today as compared to 20 years ago. You have a lot of small and medium-sized chain hoists around a lease today. You have trucks with power winches on them. You have machines that can be rigged up to be used in many ways.

Girls can drive a truck or a tractor. They can certainly drive the average pickup around a lease. They can certainly change charts, read meters, pressure gages and choke sizes. They can change choke sizes and wind clocks on your intermittent flow devices. They can use a paint brush.

So start your manpower study now. Check your age distribution by areas and by leases. Remember, you can always ship equipment from one part of the country to another by loading it on a truck or a railroad. But when you transfer a man, particularly an older man, from one part of the country to another, you have housing, family, school, and sometimes church problems involved. If you transfer an older man and he has to leave his family behind, you're asking for a lot of trouble.

Figure out how one skilled man can be used full time at his highest skill if the simpler parts of his job are taken care of by unskilled or semi-skilled workers. Analyze your work for heavy lifting or its equivalent, and see how much of it could be eliminated by substituting machinery, preferably portable equipment. Every time you can eliminate that from the picture, you are opening up a place where you can use an older man, or even a woman.

You're going to have to coddle your workers as things get tougher. We might as well be practical about it because its a real problem that we'll have to deal with. So that brings up the foreman problem.

Most authorities agree that about 90 per cent of labor troubles have their origin at the foreman level. In recent years some oil companies have made vast strides (and probably increased profits) through foremen training programs. In most cases those companies are going to be able to keep their foremen. It's a safe bet that those trained foremen are going to have less labor troubles in the tough days ahead than the foremen of companies that didn't think these training programs were profitable.

Don't overlook the fact that good foremen are going to be scarce. Your foreman is going to have to carry some heavy burdens. If he can't carry the load, you'll have to shoulder it. The best thing you can do for him right now is to see that he gets help and training along lines that other oil companies have found sound by experience.

If your foremen get some good training soon, they'll be in a lot better shape to take the grief they're going to have to carry, and they will have a lot less labor trouble. They will thank you for your foresight and be apt to stick with you, just when you need them most. Remember, the problems they can't handle will wind up on your desk.

To conclude, I want to remind you that you are engineers and that engineering principles apply to these or any other kind of problem you may face. Get the facts. Analyze the component factors in the problem. Figure out logical solutions to the various component factors. Fit these solutions together in a sound overall design. The result is an engineered design that will usually do the job — after you get a few bugs worked out. But for your own, your family, and your country's sake — design it big enough to take care of the job of the next few years. ★ ★ ★

$7,250 Contributed For Two AIME Funds

Two substantial gifts were thankfully received by the AIME Board of Directors at its meeting on Nov. 15. One was a contribution of $5,000 from the Cities Service Co., through the Doherty Memorial Fund, for special services to Petroleum Branch members. Authorization has been given to use income from the Doherty Fund to underwrite a volume on Petroleum Conservation, the manuscript of which has just been completed by Stuart Buckley, and to offset a part of the cost of publishing Petroleum Statistics annually. The same amount has also been contributed in other recent years.

A gift of $2,250 was made by the American Smelting and Refining Co., through the Seeley W. Mudd Memorial Fund, for the purchase of 1,500 copies of the volume entitled *Metal Magic*. This will be distributed free of charge to new Junior Members of the AIME in the coming year or two. ★ ★ ★

Personals

JOHN F. BINKLEY is now district engineer for the Sunray Oil Corp., Snyder, Tex. He was formerly district engineer for the Barnsdall Oil Co., Snyder.

+

KERMIT E. BROWN has accepted the position of sales and service representative, Garrett Oil Tools, Inc., Monroe, La. He was previously associated with the Stanolind Oil and Gas Co.

+

G. E. CROSBY is now a petroleum engineer with the Continental Oil Co., Hobbs, N. M. He had been petroleum engineer for the Stanolind Oil and Gas Co., Lubbock, Tex.

+

LEROY VANCE HESTER has been called back to the Army and is now stationed at Raleigh, N. C. He was a petroleum engineer for the Stanolind Oil and Gas Co., Oklahoma City, Okla.

+

J. L. LEE is now assistant general superintendent for D. D. Feldman, Oil and Gas, Dallas. He is working on drilling and production problems.

+

GERALD T. PEARSON has been named assistant regional manager, central region, production department, Continental Oil Co., Oklahoma City, Okla. He had been assistant area manager in the Fort Worth area.

+

L. MERRILL RASMUSSEN is now associated with the Canadian Gulf Oil Co., Pincher Creek, Alberta, Canada.

+

SCHOEL SCHULEMAN is now a rigger for the Perforating Guns-Atlas Corp., Houston, Tex.

JAMES H. SUTTON, junior petroleum engineer, is now relief pumper for the north structure of the Oregon Basin Field, Ohio Oil Co., Cody, Wyo.

+

LEONARD CHARLES VAN DONGEN is now connected with the Foster Wheeler Corp., Cochabamba, Bolivia.

+

GUSTAV EGLOFF, of Universal Oil Products Co., has been elected by the University of Edinburgh's Senatus Academicus to give the biennial Romanes Lecture in Chemistry for 1951. Egloff, who is vice-president of the Third World Petroleum Congress, will attend the Congress in The Hague May 28 to June 6, 1951, at which time he will lecture on "Polymerization of Olefinic Hydrocarbons."

+

ROBERT M. COOK has been appointed manager of the newly organized Strata-Crete Sales Division of Great Lakes Carbon Corp. Cook was previously vice-president and general sales manager of Security Engineering Co., and before that vice-president and general manager of International Cementers, Inc. He will maintain offices at 5845 Atlantic Ave., Long Beach, Calif.

+

ROBERT R. SHAFFER, formerly with Stanolind Oil and Gas Co. in Levelland and Odessa, Tex., is now with the Ohio Oil Co. in the capacity of field engineer. His present location is Bakersfield, Calif.

+

FLORENT H. BAILEY, RENE ENGEL, CHARLES R. DODSON and JAMES B. CHRISTIE have joined to form an organization known as International Petroleum Consultants, Ltd., with headquarters in Pasadena, Calif.

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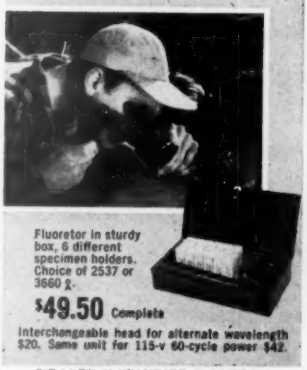

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The Geolograph Co., Inc. *Lowe Runkle Co., Oklahoma City, Okla.*	Sec. 2—5
United Geophysical Co. *Dozier-Graham-Eastman, Los Angeles, Calif.*	*
Welex Jet Services, Inc. *Albert Evans & Assoc., Ft. Worth, Tex.*	Sec. 1—1

* In previous Issues

PETROLEUM BRANCH MEETING CALENDAR

JANUARY Through JUNE

JANUARY

15	North Texas Section
17	Kansas Section
22	Pacific Petroleum Chapter
25	Oklahoma City Section

FEBRUARY

1	Illinois Basin Chapter
12	Mid-Continent Section
13	Delta Section
14	Southwest Texas Section
15	South Plains Sub-Section
15	Oklahoma City Section
19-22	AIME ANNUAL MEETING, Statler Hotel, St. Louis, Mo.
26	Pacific Petroleum Chapter

MARCH

1	Illinois Basin Chapter
12	Mid-Continent Section
13	Delta Section
14	Southwest Texas Section
15	South Plains Sub-Section
15	Oklahoma City Section
21	Kansas Section
26	Pacific Petroleum Chapter

APRIL

5	Illinois Basin Chapter
9	Mid-Continent Section
10	Delta Section
11	Southwest Texas Section
18	Kansas Section
19	South Plains Sub-Section
19	Oklahoma City Section
23	Pacific Petroleum Chapter

MAY

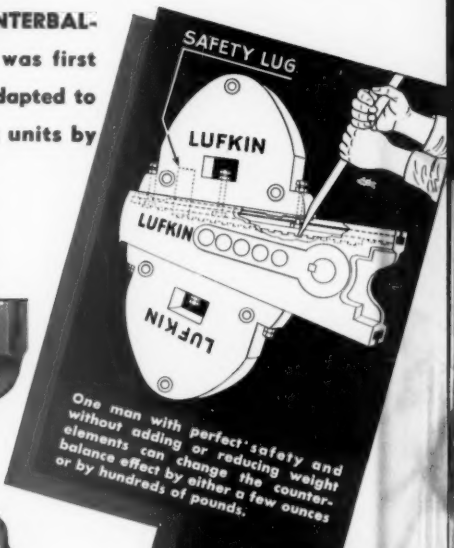
3	Illinois Basin Chapter
8	Delta Section
9	Southwest Texas Section
14	Mid-Continent Section
16	Kansas Section
17	South Plains Sub-Section
17	Oklahoma City Section
28	Pacific Petroleum Chapter

JUNE

5	Delta Section
6	Southwest Texas Section
7	Illinois Basin Chapter
11	Mid-Continent Section
20	Kansas Section
21	South Plains Sub-Section
21	Oklahoma City Section
25	Pacific Petroleum Chapter

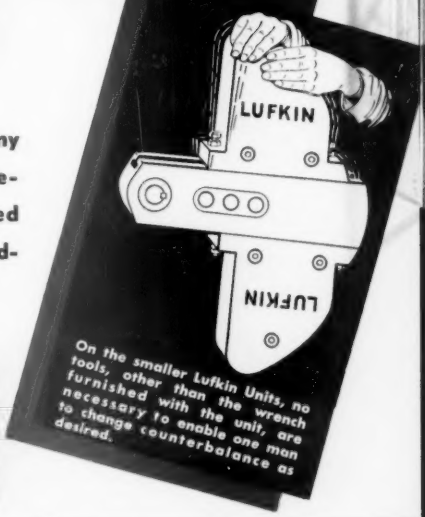
LUFKIN LEADS!

The **TROUT COUNTERBALANCED CRANK** was first introduced and adapted to oil field pumping units by **LUFKIN** in 1923.



One man with perfect safety and without adding or reducing weight elements can change the counterbalance effect by either a few ounces or by hundreds of pounds.

This crank, along with many other patented improvements, have contributed to **LUFKIN'S** imminent leadership in the industry.



On the smaller Lufkin Units, no tools, other than the wrench furnished with the unit, are necessary to enable one man to change counterbalance as desired.

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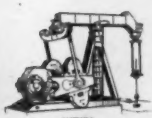
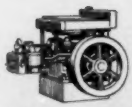
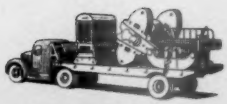

LUFKIN PUMPING UNITS


LUFKIN-COOPER-BESSEMER ENGINES


LUFKIN OIL FIELD AND INDUSTRIAL TRUCK TRAILERS

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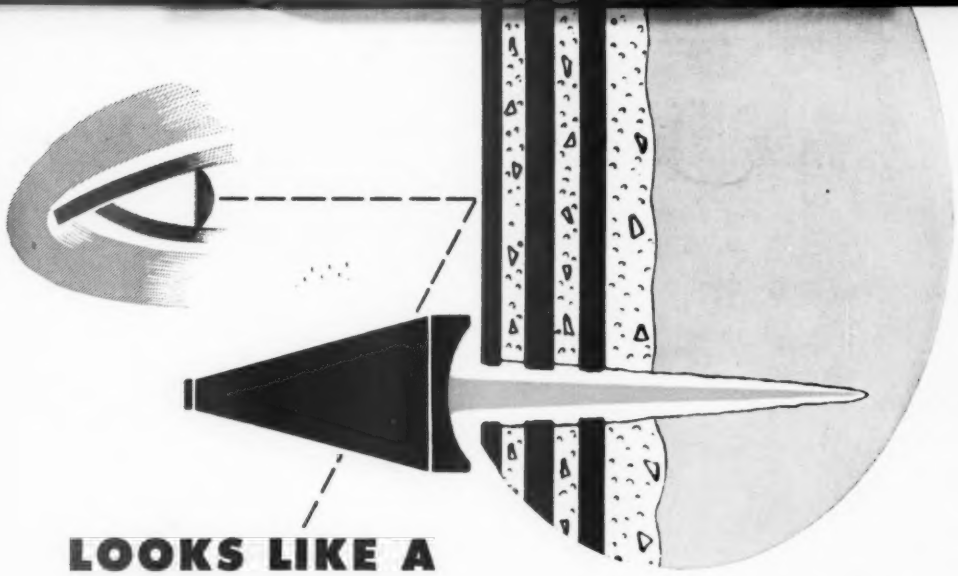
DIVISION LUFKIN FOUNDRY & MACHINE COMPANY
INDUSTRIAL, MILL AND AUTOMOTIVE SUPPLIES



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